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Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values

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1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Bechtel SAIC Company, LLC
1180 Town Center Drive
Las Vegas, Nevada 89144

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Section 6.2 of this document was developed through the contributions of Norma Biggar who performed the soil group verification analysis, created associated tables, figures, and wrote nearly all of the original drafts of the Section 6.2 analysis.

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2 Scientific Analysis Title

Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values

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	Printed Name	Signature	Date
4. Originators	Phillip Rogers	Phillip Rogers	9/8/06
	Zane Walton	Phillip Rogers for Zane Walton	9/8/06
5. Checkers	Prem Attanayake (Lead Checker)	James Kam for Prem Attanayake	9/8/06
	James Kam	James Kam	9/8/06
6. QER	Darrell Svalstad	Darrell K Svalstad	9/8/06
7. Responsible Manager/ Lead	Kenneth Rehfeldt	Kenneth Rehfeldt	9/8/06
8. Responsible Manager	Gerald Nieder-Westermann	[illegible]	09/08/2006

9. Remarks

Input regarding soil unit definition and descriptions was provided by Norma Biggar. Input regarding gravel (rock fragment) correction and uncertainty was provided by Zane Walton.

Contributing checkers: John C. Stormont (technical), Aziz Eddebbarh (technical), Edward Miller (software), and Sharad Khamamkar (data).

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ACRONYMS

DOE	U.S. Department of Energy
DTN	data tracking number
ED	Euclidean distance
FC	field capacity
GEL	Westinghouse Hanford Company Geotechnical Laboratory
GIS	Geographic Information Systems
MRC	moisture retention curve
NRCS	Natural Resource Conservation Service (USDA)
PNNL	Pacific Northwest National Laboratory
PTF	pedotransfer function
PWP	permanent wilting point
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WHC	water holding capacity
YMP	Yucca Mountain Project

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1. PURPOSE

This analysis documents the development of site-specific soil units, hydraulic parameter values for soil units, associated descriptive statistics, and uncertainties for Yucca Mountain. This work supports the U.S. Department of Energy (DOE) goal to restore credibility, traceability, and transparency to work performed by the U.S. Geological Survey (USGS) associated with the development of site-specific infiltration estimates for Yucca Mountain and to reestablish confidence in infiltration modeling prior to submittal of a license application.

This analysis has been developed in accordance with *Technical Work Plan for: Infiltration Model Assessment, Revision, and Analyses of Downstream Impacts* (BSC 2006 [DIRS 177492]). The work scope of this analysis is limited to an evaluation of the technical adequacy of the soil unit groups and their delineation in the Yucca Mountain area, and the associated hydraulic parameter values and statistics for use in infiltration modeling (BSC 2006 [DIRS 177492], Sections 1.1.2 and 1.1.3). Output from this analysis provides verification of the soil units delineated in the infiltration model (BSC 2004 [DIRS 170007]). In addition, output from this analysis provides new soil unit hydraulic parameters and descriptive statistics that are both traceable and transparent to support the development of a replacement infiltration model (BSC 2006 [DIRS 177492], Section 1.1.3).

This analysis deviates from the technical work plan (BSC 2006 [DIRS 177492], Section 9) in the use of the software code ARCINFO V.7.2.1. STN: 10033-7.2.1-00 [DIRS 157019]. ARCINFO was used in conjunction with ArcGIS Desktop V9.1. STN: 11205-9.1-00 [DIRS 176015] to process and display geospatial data associated with soil unit distributions from existing data and to support the calculation of percent area that each soil unit covers in the infiltration model area.

Soil units, soil unit hydraulic parameter values, descriptive statistics, and uncertainties developed herein describe the spatial variability of the surficial soil parameters that can affect infiltration. The output of this analysis is intended to be used as input to the simulation of net infiltration for the Yucca Mountain area.

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2. QUALITY ASSURANCE

Development of this analysis and supporting activities are subject to the Yucca Mountain Project (YMP) quality assurance program (BSC 2006 [DIRS 177492], Section 8.1). Approved quality assurance procedures (BSC 2006 [DIRS 177492], Section 4.1) have been used to conduct and document the activities of this analysis. The technical work plan also identifies methods used to control the electronic management of data (BSC 2006 [DIRS 177492], Section 8.4). Calculations have been conducted and documented following LP-SIII.9Q-BSC, *Scientific Analyses*.

This analysis examines the properties of surficial soils of the upper natural barrier, which are classified as "Safety Category" in *Q-List* (BSC 2005 [DIRS 175539], Table A-1), because they are important to waste isolation as defined in LS-PRO-0203, *Q-List and Classification of Structures, Systems, Components, and Barriers*. The calculations herein contribute to the analysis and modeling data used to support postclosure performance assessment. Conclusions herein do not affect the repository design or engineered features important to safety as defined by LS-PRO-0203.

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3. USE OF SOFTWARE

Table 3-1 lists the controlled and baselined software used in the development of this analysis.

Table 3-1. Computer Software

Software Title and Version (V)	Software Tracking Number	Code Usage and Limitations	Computer Platform, Operating System
ARCINFO V.7.2.1 [DIRS 157019]	10033-7.2.1-00	ARCINFO was used to calculate the number of cells associated with each soil type	SGI computer with IRIX 6.5
ArcGIS Desktop V9.1 [DIRS 176015]	11205-9.1.00	ArcGIS Desktop was used to plot the soil zone map and the soil sample locations	IBM PC-compatible platform with Windows® XP
JMP® Version 5, Release 5.1 (JMP 2002 [DIRS 171549])	NA	Perform statistical analysis hydraulic parameter data	IBM PC-compatible platform with Windows® 2000

NA = not applicable.

ARCINFO and ArcGIS Desktop were selected for use because they are the standard Geographic Information Systems (GIS) software used by the YMP, they use widely accepted standard GIS protocol used by the general scientific community, and they have the required capabilities to read and transform information in digital source files into the file format required for use in an infiltration model. The application of the software is appropriate for this analysis and is consistent with the intended use of the software.

The software was obtained in accordance with IT-PRO-0011, *Software Management*. The range of use for ArcGIS Desktop and ARCINFO is limited to the input and output of digital data in accordance with *Requirements Document for: ArcGIS Desktop 9.1* (DOE 2005 [DIRS 176462], Sections 2.3 and 2.5) and *Requirements Document for Arc/Info Version 7.2.1.* (CRWMS M&O 2000 [DIRS 176460], Sections 2, 3, 4, 5, and 9), respectively. The software codes were used only within the range of their validation as specified in software qualification documentation in accordance with IT-PRO-0011.

The standard functions of Microsoft® Excel® 2000, 9.0.6926 SP-3, as well as those of JMP® which are exempt commercial off-the-shelf software per IT-PRO-0011, Sections 1.4 and 1.4.6, are also used in this analysis. Excel® is used in Section 6 to calculate the area and percent that each soil covers in the area of interest, the soil hydraulic parameter descriptive statistics for each of the soil units, and the moisture retention curves using the van Genuchten equation (van Genuchten 1980 [DIRS 100610], Equation 3). Additionally, Excel® is used to manage, process, and summarize soil unit matching and tabulation of the results. JMP® is used in Section 6 and in Appendix D to plot histograms of the hydraulic parameter data and support statistical analysis of the data. Non-Q DTNs: MO0608SPAPEDOT.000 and MO0608SPANYECT.000 were prepared with the commercially available non-Q code ROSETTA (Schaap et al. 1998 [DIRS 177199]) under the guidance of *Technical Work Plan for: Infiltration Model Assessment, Revision, and Analyses of Downstream Impacts* (BSC 2006 [DIRS 177492], Sections 1.1.6, 4.2, and 8.2) and under the requirements of *Augmented Quality Assurance Program* (DOE 2004 [DIRS 171341]). The data developed with this commercially available non-Q code in these DTNs were used as indirect input for method corroboration as discussed in Appendices A and B and in Sections 6.4.5 and 6.4.6. The ROSETTA code was obtained from the YMP Software Configuration Management (SCM) software control library: Number 611352. ROSETTA was not used in the development of soil units or hydraulic parameter values.

JMP® is exempt software items in accordance with IT-PRO-0011, Section 1.4.6. JMP® is controlled by the BSC Software Configuration Management organization and were obtained from BSC Software Configuration Management. Only standard built-in functions JMP® were used.

Section 6 explains the use of the standard functions of Excel® and JMP® in sufficient detail to allow independent repetition of the calculation in accordance with LP-SIII.9Q-BSC, Attachment 2.

Specifically, Section 6 provides:

- The formula or algorithm used
- A listing of the inputs to the formula or algorithm
- A listing of the outputs from the formula or algorithm
- Narrative to describe the calculation(s).

Output DTNs: MO0605SPASOILS.005, M00605SEPDEVSH.002, MO0605SEPFCSIM.000 and MO0605SEPALTRN.000 as maintained in the Technical Data Management System by data tracking number (DTN), provides supporting Excel® calculation files. Appendices B and C provide supporting Excel® calculation files. Appendix D provides supporting JMP® calculation files.

4. INPUTS

4.1 DIRECT INPUTS

This analysis uses available data from the Technical Data Management System for verification of soil unit grouping, areal distribution, and soil grain-size distribution from laboratory analyses of samples. A collection of soil sample grain-size distribution and hydraulic parameter values developed from laboratory testing of soil samples from the DOE Hanford Site in Washington is also used as direct input. The input parameters used in this analysis and their associated sources are listed in Table 4-1. The appropriateness of these inputs for soil zone verification and soil sample hydraulic parameter calculations is discussed in Sections 4.1.1 to 4.1.4.

Table 4-1. Direct Inputs

Input Data Description	Parameter	Source
Section 6.2 Development of Representative Soil Units		
Soil units (Table 6-2)	Description of the grouping of mapped surficial deposits into soil units used in the infiltration model (BSC 2004 [DIRS 170007])	DTN: GS960408312212.005 [DIRS 146299]
Map area (Table 6-3)	Distribution of soil units in the area of interest	DTN: MO0606SPASDFIM.005 [DIRS 177030]
Section 6.3 Development of Soil Hydraulic Parameters		
Surficial map unit, soil sample texture, and rock fragment content	Sand, silt, and clay content (fraction) Rock fragment content (fraction) Surficial soil unit designation	DTN: MO0512SPASURFM.002 [DIRS 175955]
		DTN: GS031208312211.001 [DIRS 171543]
Soil sample texture for Soil Unit 6 (sand ramp sand)	Sand and silt plus clay content (fraction)	DTN: GS000383351030.001 [DIRS 148444]
Rock fragment content for Soil Unit 6	Rock fragment content (fraction)	DTN: GS940108315142.004 [DIRS 160344], p. 7
Analogous soil hydraulic parameter values	Saturated hydraulic conductivity (cm/sec)	Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B
	Moisture retention curve fitting parameters α (1/cm) and n (dimensionless)	
	Saturated moisture content, θ_s, and residual moisture content, θ_r (percent)	
	Field capacity, moisture content at −0.33 bar (−336.6 cm) and −0.10 (−102 cm) (percent)	
	Permanent Wilting point, moisture content at −60 bar (−62,200 cm) (percent)	

DTN = data tracking number.

4.1.1 Definition of Soil Units for Use in Modeling of Net Infiltration

DTN: GS960408312212.005 [DIRS 146299] defines soil units of distinct soil characteristics that could affect infiltration of precipitation into the ground. This DTN is appropriate to use because it incorporates information obtained from the mapping of surficial map units in the infiltration model area, and it groups map units having like characteristics that could affect near-surface permeability and vegetation cover into a smaller number of units, for ease of modeling (Section 6.2). The map coverage of this DTN is comparable to the area that would be included in the simulation of net infiltration for Yucca Mountain.

The grouping of surficial map units into soil units to be used in an infiltration model is portrayed as GIS output in DTN: MO0606SPASDFIM.005 [DIRS 177030]. The use of this DTN file facilitates the calculation of the percentage of total area of the model regime for each soil unit, because the GIS software can report the number of cells for each unit, as well as the total number of grid cells for the entire area of the map.

4.1.2 Surface Soil Taxonomic Unit, Soil Sample Texture, and Fraction of Rock Fragment

Qualified data and sources for taxonomic unit, textural, and rock fragment content are DTNs: GS000383351030.001 [DIRS 148444], GS031208312211.001 [DIRS 171543], and MO0512SPASURFM.002 [DIRS 175955], which contain site-specific data for the soils in the Yucca Mountain area. In particular, DTNs: GS031208312211.001 [DIRS 171543] and MO0512SPASURFM.002 [DIRS 175955] contain grain-size distributions that were determined by laboratory analyses of samples collected to characterize Soil Units 1 through 5, 7, and 9 (Section 6.2), while grain-size data for the sand ramp sand in DTN: GS000383351030.001 [DIRS 148444] is representative of Soil Unit 6. The description of eolian deposits in DTN: GS940108315142.004 [DIRS 160344], p. 7, includes a discussion of the range of rock fragment content in Soil Unit 6 (Assumption 5.1).

4.1.3 Analogous Soil Hydraulic Parameter Values

A properties report by Khaleel and Freeman (1995 [DIRS 175734]) includes a database of soil hydraulic parameters based on laboratory testing of soil samples collected from Hanford Site, which is a DOE facility located in the arid Pasco Basin in eastern Washington. The properties report (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) uses grain-size distribution, moisture retention, and saturated hydraulic conductivity from the laboratory analysis of 183 soil samples to develop and provide the following hydraulic parameters values: residual saturation (θ_r), saturation (θ_s), saturated hydraulic conductivity (K_{sat}), and the moisture-retention curve-fitting parameters, α and n. The properties report also provides moisture-retention curves developed by fitting the curves to the data using *The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils* (van Genuchten et al. 1991 [DIRS 108810]). These curves were used to estimate the field capacity (FC) and permanent wilting point (PWP). Field capacity is defined as the soil moisture content at −0.33 bar (–336.6 cm water) and at –0.10 bar (–102 cm water). Permanent wilting point is defined as the soil moisture content at –60 bar (–61,200 cm water).

Hydraulic properties are developed by matching the soil texture of Yucca Mountain soil samples to the soil texture of samples cataloged in the properties report (Khaleel and Freeman 1995 [DIRS 175734]). This is an accepted approach previously used in a DOE tank farm evaluation (JE 1999 [DIRS 176154]), Section B.1.1.2). A similar concept is incorporated into the ROSETTA program model (Schaap et al. 2001 [DIRS 176006], pp. 163 to 176) into which are input soil texture information, such as fraction of sand, silt, and clay. The program will match grain size information to a reference data set that include hydraulic parameter values.

Corroboration of developed data (Khaleel and Freeman (1995 [DIRS 175734], Appendices A and B) is provided in Section 6.4.5.

The following factors are considered to evaluate data regarding their suitability for intended use:

- Reliability of the data source
- Qualification of personnel or organizations generating the data
- Extent to which the data demonstrate properties of interest
- Prior uses of the data.

Reliability of the data source: Hanford soil samples were tested in the Westinghouse Hanford Company Geotechnical Engineering Laboratory, a facility owned and operated by the DOE, and the properties report (Khaleel and Freeman 1995 [DIRS 175734]) was peer reviewed by Dr. Rien van Genuchten of the U.S. Salinity Laboratory at Riverside, CA, and by Mark Rockhold of the Pacific Northwest National Laboratory at Richland, WA. Dr. van Genuchten is a soil physicist and research leader at the George E. Brown, Jr., Salinity Laboratory of the USDA, Agricultural Research Service in Riverside, CA. He is also an adjunct full professor of soil physics in the Department of Environmental Sciences of the University of California, Riverside. Dr. van Genuchten's experience includes over 30 years of research since receiving his PhD in 1975 from New Mexico State University; his major professor was Dr. Peter Wierenga. Dr. van Genuchten has authored or coauthored approximately 300 research publications, including two books of which one is in Japanese, and five edited texts. Dr. Rockhold is a staff scientist with Pacific Northwest National Laboratory at Richland, WA. He is an experienced soil scientist with site-specific knowledge of the Hanford environment.

Qualification of personnel or organizations generating the data: Dr. Raziuddin Khaleel has over 30 years of experience in vadose zone and groundwater hydrology and numerical simulations of subsurface flow and transport. He was a key contributor to Hanford solid waste performance assessments and the immobilized low-activity waste performance assessment, particularly in the area of conceptual model development and direction of modeling. He also served as adjunct faculty for the Civil and Environmental Engineering Department of Washington State University Tri-Cities Campus in Richland, WA. He earned a BS in civil engineering from Bangladesh University of Engineering and Technology in 1966, an MS in water science and engineering from Asian University of Technology in Thailand in 1970, and a PhD in soil and water engineering from Texas A&M University in 1977. Eugene Freeman is the second author on the paper and is a qualified analyst. Mr. Freeman holds an MS in hydrology from University of Idaho (1995), a BS in geology from Montana State University (1986), and is a licensed professional geologist and hydrogeologist in Washington.

Extent to which the data demonstrate the properties of interest: Data provided in the properties report (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) include saturated hydraulic conductivity, soil moisture at a range of matric potential, and moisture retention curve fitting parameters that would be used as input to several infiltration modeling approaches including the one developed for Yucca Mountain. These data are developed from soil and sediment samples collected at Hanford where soils have developed under arid climatic conditions similar to that of Yucca Mountain. The average annual precipitation at Hanford is about 17.3 cm/yr (DOE 2001 [DIRS 177079], Section 3.2) compared to about 12.5 cm/yr for Yucca Mountain (BSC 2004 [DIRS 169734], Section 3.42).

Hanford sediments have organic carbon content below 0.5 wt% (Truex et al. 2001 [DIRS 177078], Section 2.3.1.2). Organic carbon content in agricultural areas of Nye County range from about 0.006% to 0.70% (USDA 2006 [DIRS 176439]). Soil textural information provided in the properties report (Khaleel and Freeman 1995 [DIRS 175734], Appendix A) is directly comparable to soils information in DTNs: MO0512SPASURFM.002 [DIRS 175955], GS031208312211.001 [DIRS 171543], and GS000383351030.001 [DIRS 148444].

The soil depositional processes at Yucca Mountain compared to those at Hanford include some differences, which can contribute to differences in grain shape and soil structure. Large-scale fluvial processes dominate Hanford soil and sediments resulting in more-rounded particles and single-grain structure. Small-scale fluvial processes and eolian (Soil Unit 6) are the dominant processes at Yucca Mountain, resulting in less-rounded particles with more angular fragments. Soils of fluvial origin associated with Soil Units 1 through 4 (stream and alluvial fan material) cover over 40% of the infiltration model area. There is an eolian component that has accumulated on these surfaces through time, which is concentrated in the upper 0.5 to 1 m of the soil profile. Deposits representing eolian source material are mapped over only 4.8% of the area (Soil Unit 6). The dominant surficial deposit (54% of the model area; Soil Units 5, 7, and 9) is colluvium. The colluvium consists of rock fragments of parent material that have been separated from the underlying intact bedrock through weathering processes. Colluvium, however, by definition, does not remain in situ, but moves or has moved, or both, downslope through gravitational processes. The fine-grained component of colluvial soils is interpreted to be due to the influx of eolian material.

There are depositional mode differences between the YMP soils and Hanford soils and sediments; the differences in the associated hydraulic parameters, however, are not quantified because there are no site-specific hydraulic data for Yucca Mountain. Such differences contribute to an overall uncertainty, captured by the development of descriptive statistics for each hydraulic parameter that includes the parameter mean and standard deviations (Section 6.3).

Prior uses of the data: Similar applications of data (Khaleel and Freeman 1995 [DIRS 175734]) include the use of hydraulic parameter values extracted from data for the vadose zone flow and transport modeling by Kincaid et al. (1998 [DIRS 176155], Section 4.1.2.1.2 and Table 4.7). Kincaid et al. (1998 [DIRS 176155]) were prepared to provide an estimate of the cumulative radiological impacts of waste and disposal actions at Hanford. Soil hydraulic parameter data (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) were used as direct input into vadose zone flow and transport models that were integral to developing cumulative impacts (Kincaid et al. 1998 [DIRS 176155], Section 4.1.2.1.2 and Table 4.7).

The tank farm evaluation (JE 1999 [DIRS 176154]) was prepared by the DOE to develop methodologies and to identify data needs required for supporting tank waste retrieval and closure decisions. Underlying calculations used to develop the retrieval and closure methodologies include vadose zone flow and contaminant transport. A soil texture matching approach (JE 1999 [DIRS 176154]), Section B.1.1.2) combined with data presented in the properties report (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) were used to develop soil hydraulic parameters for direct input into vadose zone flow and contaminant transport models (JE 1999 [DIRS 176154], Table B.1.1).

4.2 CRITERIA

An infiltration model is one component of the total system performance assessment of Yucca Mountain. General requirements to be satisfied by the total system performance assessment are stated in 10 CFR 63.114 [DIRS 176544]. Acceptance criteria used by the U.S. Nuclear Regulatory Commission to determine whether the technical requirements of 10 CFR 63.114(a) to (c) and (e) to (g) [DIRS 176544] have been met, with regard to the adequacy of an infiltration model, are listed in NUREG-1804 (NRC 2003 [DIRS 163274], Section 2.2.1.3.5.3).

Acceptance criteria relating to the climate and net infiltration model abstraction that are applicable to soil data input to the infiltration model are (NRC 2003 [DIRS 163274], Section 2.2.1.3.5.3):

- Acceptance Criterion 1: *System Description and Model Integration are Adequate*

  The aspects of geology, hydrology, geochemistry, physical phenomena, and couplings, that may affect climate and net infiltration, are adequately considered. Conditions and assumptions in the abstraction of climate and net infiltration are readily identified and consistent with the body of data presented in the description.

- Acceptance Criterion 2: Data are Sufficient for Model Justification

  Climatological and hydrological values used in the license application (e.g., time of onset of climate change, mean annual temperature, mean annual precipitation, mean annual net infiltration, etc.) are adequately justified. Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided.

  Estimates of present-day net infiltration using mathematical models at appropriate time and space scales are reasonably verified with site-specific climatic, surface, and subsurface information.

  The effects of fracture properties, fracture distributions, matrix properties, heterogeneities, time-varying boundary conditions, evapotranspiration, depth of soil cover, and surface-water runoff and run-on are considered, such that net infiltration is not underestimated.

- Acceptance Criterion 3: *Data Uncertainty is Characterized and Propagated through the Model Abstraction*

  Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in an under-representation of the risk estimate.

  The technical bases for the parameter values used in this abstraction are provided.

  Possible statistical correlations are established between parameters in this abstraction. An adequate technical basis or bounding argument is provided for neglected correlations.

4.3 CODES, STANDARDS, AND REGULATIONS

No codes, standards, or regulations other than those identified in Section 4.2 are applicable to this work. There are no industrial or technical standards directly applicable to this work activity.

5. ASSUMPTIONS

The following assumptions were developed in the absence of direct data for use as input to the analysis. In addition, scientific assumptions are presented in Section 6.

5.1 ROCK FRAGMENT CONTENT OF SOIL UNIT 6

Assumption: For the purposes of developing soil hydraulic parameter values for Soil Unit 6, it is assumed that the unit contains 27% rock fragments.

Basis: All soil units in the infiltration model area contain rock fragments and, as discussed in Sections 4.1.4 and 6.3.3, corrections are made in the analysis to address the effect of the rock fragments on soil hydraulic properties. With the exception of Soil Unit 6, laboratory data regarding the percentage of rock fragments in measured samples were available for making the corrections. Although the description of Soil Unit 6 includes a statement that the unit contains 5% to 50% rock fragments (Section 6.2), the textural data for Soil Unit 6 in DTN: GS000383351030.001 [DIRS 148444] are for samples that had already been sieved, and the rock fragments have been removed and were not recorded. For the purposes of this analysis, a value of 27% is assumed, which is the midpoint between 5% and 50% rounded down to the nearest whole number. The effect associated with this assumption is small because Soil Unit 6 comprises less than 5% of the soils in the infiltration model area (Section 6.2). The closest occurrence of Soil Unit 6 is approximately 1.5 mi east of the lower extent of the projected repository footprint (Section 6.2) and there are no occurrences of Soil Unit 6 over the projected repository footprint.

Where used: This assumption is discussed in Section 6.3.3 and is used in Section 6.3.4.

5.2 PEDOGENIC CARBONATE IMPACT ON SOIL HYDRAULIC PARAMETERS

Assumption: It is assumed that the accumulation of pedogenic carbonate in the soil units is insufficient to significantly affect the overall soil conductivity parameter values for the infiltration model area, and that the pedogenic carbonate that is present in soils, if considered, would reduce the rate of infiltration into the underlying bedrock.

Basis: Field descriptions from the mapping of surficial deposits (Section 6.2) provide a qualitative assessment of the amount of pedogenic carbonate that has accumulated in soils in the infiltration model area (Section 6.2; Table 6-4). Field descriptions (Table 6-4) indicate that the pedogenic carbonate accumulated in most of the surficial map units is Stage III or less where carbonate accumulation stages are defined in footnote (h) on Table 6-4. Stage III carbonate soils in gravelly deposits have a maximum $CaCO_3$ content of 10% to 25% (Machette 1985 [DIRS 104660], Table 1); soils having this amount of carbonate accumulation cover 17% of the map area. Only Soil Unit 1, which is mapped in 8% of the infiltration model area, consistently exhibits a higher stage of development (Stage IV) with regard to carbonate soils (Section 6.4.1; Table 6-4). The maximum $CaCO_3$ content of Stage IV gravelly soils is on the order of 50% (Machette 1985 [DIRS 104660], Table 1).

Laboratory data provide a measure of K_{sat} for the Stage IV soils and, thus, also provide a bounding value for this parameter in soils having less well-developed carbonate soils. Measurement results of fracture-filling caliche are reported in DTN: GS950708312211.003 [DIRS 146873], Table S98356_004. Saturated hydraulic conductivity was measured on 15 subsamples from five samples of fracture-filling material. The caliche in the fractures is formed by precipitation of minerals from water on the fracture walls as it evaporates. As a result, it is vertically "layered" and measurements are reported for samples collected both parallel to and perpendicular to the layers. The eleven measurements that are in the perpendicular direction are considered representative of laminar Stage IV carbonate soil. These measurements have a geometric mean of 1.09E-06 cm/sec, which is approximately two orders of magnitude lower than the values derived for the soil units in Section 6.3. Saturated hydraulic conductivity values for soils exhibiting Stage I and Stage II carbonate soils would fall between the value allocated to Stage IV soils and those calculated for soils without considering carbonate content (Section 6.3), meaning that the values would be lower than the calculated values, but within two orders of magnitude.

Where used: This assumption is applied to the development of hydraulic parameters for the soil units of the infiltration model area (Section 6.3). The qualitative field observations of carbonate content are compared against laboratory measurements (Section 6.4.1) in assessing the contribution of this assumption to the uncertainty in results.

5.3 FIELD CAPACITY

Assumption: It is assumed that FC is the soil moisture content at which internal drainage ceases based correlation to matric potentials of −0.33 bar and −0.10 bar.

Basis: Field capacity has been defined as the soil moisture content at which internal drainage ceases based on observations that the rate of flow and water-content changes decrease with time after a precipitation or irrigation event (Hillel 1980 [DIRS 100583], p. 67). This concept, however, was recognized as arbitrary and is not an intrinsic soil property independent of the way it is measured (Hillel 1980 [DIRS 100583], p. 68). This concept is most tenable on coarse-textured soils in which internal drainage is initially most rapid but soon slows down owing to the relatively steep decrease of hydraulic conductivity with increased matric suction (Hillel 1980 [DIRS 100583], p. 68). Although matric potentials of −0.33 bar or −0.10 bar have been used to correlate measurements of soil moisture storage in the field, these criteria do not apply universally to all soils and all conditions (Hillel 1980 [DIRS 100583], p. 70). An alternative approach from NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], p. 6) using arguments by Hillel (1980 [DIRS 100583], pp. 67 to 72) defines FC as the drainage rate considered negligible, which is a function of the intended application. NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], p. 6) suggests using an unsaturated hydraulic conductivity equal to 10^{-8} cm/sec. The weakness inherent with this approach is determining the definition of negligible flux.

For the development of inputs to an infiltration model, the FC values based on both matric potentials of –0.33 bar and –0.10 bar are developed to capture the uncertainty inherent with the FC concept. FC, as measured with the matrix potential criteria, is reported to vary from about 4% to 45% (Hillel 1980 [DIRS 100583], p. 72). With criteria of either –0.33 bar or –0.10 bar, some unrealistically low values of FC, on the order of 0.01 or less, are obtained (Section 6.3.4). Soil texture tends to be coarse for many Yucca Mountain samples, which is why the –0.10 bar criterion results in fewer unrealistic FC values compared to the –0.33 bar criterion.

Where used: This assumption is applied to the development of FC and water holding capacity (WHC) for the soil units of the infiltration model area (Section 6.3).

5.4 ROCK FRAGMENT CORRECTION

Assumption: It is assumed that laboratory measurements of moisture content and K_{sat} are adequately adjusted for the presence of rock fragments 2 mm and greater.

Basis: Vadose zone soils in desert environments often contain high gravel or rock fragment fractions which are defined as fragments greater than 2 mm in size (Khaleel and Relyea 1997 [DIRS 175733]). Laboratory measurements of moisture retention and K_{sat} are typically made on the fine fraction (less than 2 mm size) material and then corrected for field conditions by accounting for the gravel or rock fragment fraction in the sample. Moisture contents for bulk (soil and gravel) samples are lower than corresponding values for the same sample containing no rock fragments (Khaleel and Relyea 1997 [DIRS 175733], p. 1875). Likewise, K_{sat} values for bulk (soil and gravel) samples are lower than corresponding values for the same sample containing no rock fragments (Brakensiek and Rawls 1994 [DIRS 175944], Equation 23). For the development of inputs to an infiltration model, the laboratory-derived moisture content and K_{sat} values from the analogous database are adjusted (Section 6.3.3) to represent YMP site conditions.

Where used: This assumption is directly applied to the development of moisture contents associated with θ_s, PWP, and FC and values of K_{sat} for the soil units of the infiltration model area (Section 6.3). It is indirectly applied to the WHC because it is the difference in moisture content between the FC and PWP (Section 6.3).

5.5 PERMANENT WILTING POINT

Assumption: The PWP is the soil moisture content below which plants are unable to withdraw soil moisture and is assumed to correspond to −60 bar soil matric potential.

Basis: Permanent wilting point is defined as the soil moisture content below which plants are unable to withdraw soil moisture. At the PWP, the potential of plant roots to absorb water is balanced by the water potential of the soil. PWP depends on plant properties, soil properties, and meteorological conditions. Generally, in agricultural applications, PWP is assumed to be the soil water content corresponding to a −15 bar matric potential.

The soil moisture content corresponding to −60 bar matric potential is more appropriate for the Yucca Mountain infiltration area because of the indigenous plant community. The −60 bar matric potential is consistent with the lower limits of soil moisture extraction determined for several Mojave Desert shrubs that can survive soil water potentials as low as −50 to −100 bar (Bamburg et al. 1975 [DIRS 127392], Figures 1 and 2; Hamerlynck et al. 2000 [DIRS 177022], Figure 3; Hamerlynck et al. 2002 [DIRS 177046], Figure 6; Odening et al. 1974 [DIRS 177026], pp. 1089 to 1090; Smith et al. 1997 [DIRS 103636], pp. 95, 110, 115, and 116).

Where used: This assumption is applied to the development of PWP and WHC for the soil units of the infiltration model area (Section 6.3).

6. SCIENTIFIC ANALYSIS DISCUSSION

6.1 INTRODUCTION

This section documents the technical approach used to verify the distribution of soil units across the Yucca Mountain infiltration model area and to develop hydraulic parameter values and associated statistics for those soil units. The spatial distribution of soil units and their hydraulic properties are input to the analysis of net infiltration from precipitation at Yucca Mountain. The definition of the soil units is based on mapping of surficial deposits in the Yucca Mountain area. DTN: GS960408312212.005 [DIRS 146299] groups approximately 40 surficial deposit map units into 10 soil units to create a surficial properties/hydrologic properties map for input into subsequent infiltration modeling. Rationale for grouping surficial mapping units into soil units was not provided in DTN: GS960408312212.005 [DIRS 146299]. Hence, the definition of the soil units is reviewed to assess the appropriateness of the grouping (Section 6.2) and rationale is provided for the grouping.

Section 6.3 discusses the development of hydraulic parameters for the Yucca Mountain soil units. This analysis uses empirical data available for soil units, including grain-size distribution and fraction of rock fragments. These data were derived from laboratory analysis of soil samples collected from Yucca Mountain soil units (DTNs: GS031208312211.001 [DIRS 171543], MO0512SPASURFM.002 [DIRS 175955], and GS000383351030.001 [DIRS 148444]). Representative hydraulic parameter values of each of the soil units are developed by matching the texture of samples from Yucca Mountain soil units to similar soil textures in an analogous site database (Khaleel and Freeman 1995 [DIRS 175734]). In the analogous site database, hydraulic parameters have been determined for soil samples that are characterized by particle size data (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B). Technical inputs used directly in the calculation of the hydraulic parameters for the Yucca Mountain soil units are listed in Table 4-1. Indirect inputs of corroborative or supporting information for this analysis are provided as Table 6-1. Soil unit distributions, hydraulic parameters, and associated statistics developed herein include spatial variability and are only intended for use as input to an infiltration model.

Table 6-1. Indirect Inputs

Technical Product Input Source	Specifically Used From	Specifically Used In	Input Description
10 CFR Part 63 [DIRS 176544]	Entire	Section 4.2	Description of general requirements to be satisfied by the TSPA
ARCINFO [DIRS 157019]	Entire	Section 1	General reference to software used in analysis
Bamberg [DIRS 127392]	Figures 1 and 2	Sections 5.5 and 6.3.	Background for development of permanent wilting point for several Mojave Desert shrubs
BSC 2004 [DIRS 169734]	Section 3.42	Sections 4.1.3, 6.3, and 6.4.4	Average annual rainfall for Yucca Mountain area
BSC 2005 [DIRS 175539]	Table A-1	Section 2	Classification of safety category for natural barriers

Table 6-1. Indirect Inputs (Continued)

Technical Product Input Source	Specifically Used From	Specifically Used In	Input Description
BSC 2006 [DIRS 176355]	Entire	Sections 6.2.3.2 and 7.1.1	General reference to analysis of bedrock permeability
BSC 2006 [DIRS 177492]	Entire, Sections 1.1.2 and 1.1.3	Sections 1 and 2	Technical plan governing analyses conducted
Carsel and Parrish 1988 [DIRS 147295]	Entire	Sections 6.3, 6.3.4.1, 6.4.5, and 6.4.6; Table 6-14	Describes empirical approach for estimating soil hydraulic parameter values from textural classes
Cornelis et al. 2001 [DIRS 176383]	Entire	Section 6.4.4	Discussion of development and use of pedotransfer function
Cronican and Gribb DIRS [177039]	Entire	Section 6.4.5	Gravel correction method for soil samples with sand ranges greater than 70%
CRWMS M&O 2000 [DIRS 176460]	Sections 2, 3, 4, 5, and 9	Section 3	Input or output requirements, performance requirements, user and software interface requirements, and data requirements
DOE 2001[DIRS 177079]	Sec 3.2	Sections 4.1.3, 6.3, and 6.4.4	Average Annual Precipitation at Hanford
DOE 2005 [DIRS 176462]	Sections 2.3 and 2.5	Section 3	Software design constraints and input/output requirements
Domenico and Schwartz 1990 [DIRS 100569]	p. 67	Sections 6.3.4 and 7.1.2	Explains how hydraulic conductivity is best represented by the geometric mean
DTN: GS031208312211.001 [DIRS 171543]	Entire	Sections 6.4.1 and 6.4.2; Table 6-13; Figure 6-11	Identification of procedures used to collect and analyze samples and measured calcium carbonate content in soil samples
DTN: GS940108315142.004 [DIRS 160344]	Entire; p. 11 of 13	Sections 6.2.1, 6.2.3.2, 6.2.4, and 6.2.5; Table 6-4	One of four surficial deposits maps used in developing soil units for the infiltration model (BSC 2004 [DIRS 170007])
DTN: GS940108315142.005 [DIRS 160345]	Entire	Sections 6.2.1, 6.2.3.2, and 6.2.5; Table 6-4	One of four field surficial deposits maps used in developing soil units for the infiltration model (BSC 2004 [DIRS 170007])
DTN: GS940708315142.008 [DIRS 160346]	Entire	Sections 6.2.1, 6.2.3.2, and 6.2.5; Table 6-4	One of four surficial deposits maps used in developing soil units for the infiltration model (BSC 2004 [DIRS 170007])
DTN: GS950408315142.004 [DIRS 160347]	Entire	Sections 6.2.1 and 6.2.5; Table 6-4	One of four field surficial deposits maps used in developing soil units for the infiltration model (BSC 2004 [DIRS 170007])
DTN: GS950708312211.003 [DIRS 146873]	Table S98356_004	Sections 5.2 and 6.4.1	Measured saturated hydraulic conductivity for fracture-filling caliche.
DTN: MO0509COV00029.000 [DIRS 175946]	Coverage name: SURFDEPQS	Section 6.2.1	Composite surficial deposits map for the Yucca Mountain area
DTN: MO0512SPASURFM.002 [DIRS 175955]	Entire	Sections 6.1, 6.4.2, and 6.4.4	General reference regarding soil texture and soil unit information, and identification of procedures used to collect and analyze samples

Table 6-1. Indirect Inputs (Continued)

Technical Product Input Source	Specifically Used From	Specifically Used In	Input Description
Duniway et al. 2004 [DIRS 176417]	Entire	Sections 6.2.3.1 and 6.4.1	Study of effects of pedogenic carbonate in soil
Freeze and Cherry 1979 [DIRS 101173]	Table 2.2; Sections 2.4 and 8.7	Sections 6.4.1 and 6.3.4.1	Estimates of hydraulic conductivity based on grain size and formation and K_{sat} distribution
Gelhar [DIRS 101388]	pp. 1 and 2	Sections 6.3.4.1, 6.3.4.2, and 6.3.4.3.	Distribution and variation of hydraulic conductivity
Hamerlynck [DIRS 177022]	p. 600 and Figure 3	Sections 5.5 and 6.3.	Lower limits of soil moisture extraction determined for several Mojave Desert shrubs
Hamerlynck et al. 2002 [DIRS 177046]	Figure 6	Section 5.5 and 6.3 and Table 6-1	Discussion of lower limits of soil moisture extraction for several Mojave Desert shrubs
Hillel 1980 [DIRS 100583]	Pages 67-72	Sections 5.3 and 6.3	Discussion of the field capacity concept and definitions
Istok et al. 1994 [DIRS 176890]	Entire	Sections 6.3.4.1 and 6.4.7 and Table 6-19	Description of soil investigations and results at NTS
JE 1999 [DIRS 176154]	Entire; Section B.1.1.2; Table B.1.1	Sections 4.1.3 and 6.3	Describes soil texture matching approach and support the use of a direct input for its intended use
Keefer et al. 2004 [DIRS 173899]	Chapter 2, Tables 2 and 3	Sections 6.2.1 and 6.2.3.2; Tables 6-2 and 6-4; Figures 6-2 to 6-9	Summary descriptions of surficial deposits in the Yucca Mountain area
Khaleel and Freeman 1995 [DIRS 175734]	Entire; p. iii; Equation 5, Sections 1, 2.0, 3.2 to 3.4, 5.1; Appendices A and B	Sections 4.1.3, 6.1, 6.3 to 6.3.4, 6.4, 6.4.2 to 6.4.4, 6.4.6, 6.4.8, 7.1.2 and 7.3	General reference to source of soil hydraulic parameter values, approach and methodology used, moisture content correction for gravel content, and corroboration of approach
Khaleel and Relyea 1997 [DIRS 175733]	Entire; Equation 2; p. 1875	Sections 5.4 and 6.3.3	Justification for corrections associated with rock content
Kincaid et al. 1998 [DIRS 176155]	Entire; Section 4.1.2.1.2; Table 4.7	Section 4.1.3	Supports prior use of a direct input
Lundstrom et al. 1995 [DIRS 104657]	Entire	Section 6.2.1	Composite descriptions of surficial deposits in the Yucca Mountain area
Nemes et al. [DIRS 177511]	p. 327	Section 6.3	Describes various PTF approaches
NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004])	Entire; pp. 5 and 6; Sections 2, 2.2 and 5; Figure 6-1; Tables 2-1, A-1 to A-3 and B-1 to B3; Appendices A and B	Sections 5.3, 6.3, 6.3.4.1, and 6.4.5; Tables 6-8, 6-10, and 6-14	Statistical distribution of soil hydraulic parameters
NRC 2003 [DIRS 163274]	Section 2.2.1.3.5.3	Sections 4.2 and 7.4; Table 7-2	Acceptance criteria

Table 6-1. Indirect Inputs (Continued)

Technical Product Input Source	Specifically Used From	Specifically Used In	Input Description
NWM-USGS-GP-17, R1	Entire	Section 6.4.1	Procedure used by USGS to collect soil samples
NWM-USGS-HP-259, R0	Entire	Section 6.4.1	Describes process used to determine bulk density of soils
NWM-USGS-HP-263, R0	Entire	Section 6.4.1	Procedure used by USGS to conduct particle size analysis of soil samples
NWM-USGS-HP-265, R0	Entire	Section 6.4.1	Procedure used by USGS to determine calcium carbonate content of soil samples
NWM-USGS-HP-265, R0-M1	Entire	Section 6.4.1	Procedure used by USGS to determine calcium carbonate content of soil samples
NWM-USGS-HP-265, R0-M2	Entire	Section 6.4.1	Procedure used by USGS to determine calcium carbonate content of soil samples
Odening et al. 1974 [DIRS 177026]	pp. 1089-1090	Sections 5.5 and 6.3	Lower limits of soil moisture extraction determined for several Mojave Desert shrubs
Resource Concepts 1989 [DIRS 103450]	Entire; Figure 2; Table 1	Sections 6.2.3.2 and 6.2.4; Figure 6-10; Table 6-5	Soil classification for Yucca Mountain soils
Schaap et al. 2001 [DIRS 176006]	Entire; pp. 163 to 176	Sections 4.1.3, 6.3, 6.4.4, 6.4.5, 6.4.6, and 7.3; Table 6-16	Hydraulic property estimator used to support use of another reference as direct input and in discussion of uncertainties
Swan et al. 2001 [DIRS 158784]	pp. 8 to 21	Sections 6.2.1 and 6.2.3.2; Table 6-4; Figures 6-2 to 6-9	Description of surficial deposits in the Yucca Mountain area
Truex et al. 2001 [DIRS 177078]	Sec 2.3.1.2	Sections 4.1.3, 6.3, and 6.4.4	Organic carbon content of Hanford sediments.
USDA 1999 [DIRS 175948]	Map: Dominant Soil Orders; Chapters 11 and 12; p. 48	Sections 6.2.3.1, 6.2.3.2, and 6.4.1	General reference to the USDA soil taxonomy system. Soil orders found in Yucca Mountain area.
USDA 1999 [DIRS 152585]	Exhibit 618-8	Section 6.3.4.1 and Table 6-17	Soil triangle and properties of soils
USDA 2003 [DIRS 175947]	Chapters 7 and 8	Section 6.2.3.2	Soil taxonomy
USDA 2004 [DIRS 173916]	Busted Butte quadrangle	Section 6.2.4 and Figure 6-10	Areal extent of mapped soil associations
	Entire	Section 6.2.4	General reference to the Nye County soil survey
	pp. v, vi, 259, 285, 315, 322, 336, 347, and 349	Table 6-5	Taxonomic names for mapped soil associations
USDA 2006 [DIRS 176439]	Entire	Sections 4.1.3, 6.3, 6.4.3, 6.4.4, 6.4.6 and 7.3; Appendix C	Nye County soil sample texture, bulk density, and moisture at selected matric potentials
USDA 2006 [DIRS 177049]	Entire	Appendix C	Nye County soil void ratio data

Table 6-1. Indirect Inputs (Continued)

Technical Product Input Source	Specifically Used From	Specifically Used In	Input Description
USDA 2006 [DIRS 177088]	Entire	Section 6.4.7 and Appendix C	Nye County soil sample data
USGS 2003 [DIRS 177192]	Page 2	Section 6.4.5	Results using ROSETTA as reported in study by the USGS
van Genuchten 1980 [DIRS 100610]	Entire; Equation 3	Sections 3 and 6.4.6	Relationship between matric potential and moisture content in partially saturated soils
van Genuchten et al. 1991 [DIRS 108810]	Entire	Sections 4.1.3, 6.3, 6.3.1, 6.4.3, and 6.4.5	Documentation of software used for calculating moisture retention curves
YMP-USGS-HP-259, R0-M1	Entire	Section 6.4.1	Procedure used by USGS to determine bulk density
YMP-USGS-HP-259, R0-M2	Entire	Section 6.4.1	Procedure used by USGS to determine bulk density of samples
YMP-USGS-HP-263, R0-M1	Entire	Section 6.4.1	Procedure used by USGS to conduct particle-size analysis of soil samples
Young et al. 2004 [DIRS 176416]	Entire; Figure 5	Sections 6.2.3.1 and 6.4.1	Description of the influence of age on the infiltration capability of soils

TSPA = total system performance assessment; USDA = U.S. Department of Agriculture; USGS = U.S. Geological Survey.

6.2 DEVELOPMENT OF REPRESENTATIVE SOIL UNITS

6.2.1 Mapping of Surficial Deposits in the Infiltration Model Area

DTN: GS960408312212.005 [DIRS 146299] uses attributes of surficial deposits to group similar mapped surficial deposits into a smaller number of soil units (Table 6-2) to describe the movement of precipitation from the ground surface to the subsurface. Ten soil units were identified in DTN: GS960408312212.005 [DIRS 146299], representing a grouping of the surficial mapping units from the following DTNs:

- GS940108315142.004 [DIRS 160344]
- GS940108315142.005 [DIRS 160345]
- GS940708315142.008 [DIRS 160346]
- GS950408315142.004 [DIRS 160347].

These DTN sources identify 31 surficial map units, from which data were combined into one composite map of the geographical area (DTN: MO0509COV00029.000 [DIRS 175946], coverage name: SURFDEPQS). Nine new map units were created, for a total of 40 map units, by combining individual units into a new unit without eliminating the original units. For example, a new callout of Soil Units 5 to 7 was added, in addition to retaining Surficial Map Units 5 and 7. The surficial map units, from the composite Yucca Mountain surficial deposits map, were grouped into soil units that could be used in the modeling of net infiltration in DTN: GS960408312212.005 [DIRS 146299] (Table 6-2).

Table 6-2. Soil Units Combined from Mapped Surficial Units

Soil Unit[a]	Surficial Map Unit[a]	Type of Deposit[b]	Soil Taxonomic Name[a]
1	0, 1[c], 1 to 3, 2[c] Tgp	Fluvial	Typic Argidurids
2	3[c], 3?, 3f, 3 to 4, 4[c], 4f, 4s, 4/1, 4s	Fluvial	Typic Haplocalcids
3	5[c], 5f, 5s, 5/1, 5 to 6, 5f to 6f, 6[c], 6f, 5[c] to 7[c]	Fluvial	Typic Haplocambids
4	7[c], 7f, 6 to 7, 6f to 7f	Fluvial	Typic Torriorthents
5	cu[c], cs	Colluvium	Lithic Haplocambids
6	e, eo, ey, 1/e, 3/e, cf/e	Eolian	Typic Torripsamments
7	rc[c]	Colluvium	Lithic Haplargids
8	r	Bedrock	Rock
9	cf[c]	Colluvium	Typic Calciargids
10	d	Disturbed	Disturbed Ground

[a] DTN: GS960408312212.005 [DIRS 146299], Data Summary Sheet.

[b] Surficial Map Unit 7 is the equivalent to unit Qa7 by Keefer et al.(2004 [DIRS 173899], Chapter 2); similarly, Surficial Map Unit 6 = Qa6, Surficial Map Unit 5 = Qa5, Surficial Map Unit 4 = Qa4, Surficial Map Unit 3 = Qa3, Surficial Map Unit 2 = Qa2, Surficial Map Unit 1 = Qa1, and Surficial Map Unit 0 = QT0.

[c] Surficial map units for which laboratory data are available.

Field mapping of surficial deposits uses the extent of soil development, geomorphic character, and topographic position of surficial deposits as primary criteria for defining map units, as these features provide relative ages of deposits. These field observations were summarized by Lundstrom et al. (1995 [DIRS 104657]). Individual map descriptions from DTNs: GS940108315142.004 [DIRS 160344], GS940108315142.005 [DIRS 160345], GS940708315142.008 [DIRS 160346], and GS950408315142.004 [DIRS 160347] were combined into one set of descriptions for mapped surficial deposits (Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21). Laboratory analyses of samples, representing the different surficial map units, were evaluated (Lundstrom et al. 1995 [DIRS 104657]) to further characterize and differentiate the units.

The primary use of the surficial deposits mapping for the YMP has been in the assessment of seismic risk from earthquake faults, where the geologic age of a deposit that is or is not offset by a fault is important. Laboratory analyses conducted on samples collected from the deposits of varying field-interpreted ages were used to further characterize the deposits and to support the age assignments. These empirical data represent the bulk of the information that was available for the analyses for developing hydraulic parameters (Section 6.3). The collection of these data focused on the fluvial deposits of Surficial Map Units 1 to 7 (Soil Units 1 to 4), as they are commonly comprised of stratigraphically distinct horizons useful for interpreting Quaternary faulting history.

6.2.2 Definition of Soil Units for Infiltration Modeling

The geographical extent of the 10 soil units (Table 6-2) is shown in Figure 6-1, which is reproduced from DTN: MO0606SPASDFIM.005 [DIRS 177030]. The cumulative extent of each map unit was calculated using DTN: MO0606SPASDFIM.005 [DIRS 177030] and ARCINFO (Table 6-3).

Distinguishing characteristics of the surficial map units that lead to the grouping of these units into soil units for infiltration modeling are summarized in Table 6-4. Table 6-4 also provides the correlation of mapped surficial deposits to soil units in DTN: GS960408312212.005 [DIRS 146299]. Table 6-4 is organized by type of deposit (fluvial, eolian, or colluvial) and apparent age of the deposit, with Surficial Map Unit 7 being the youngest fluvial deposit and Surficial Map Unit 0 being the oldest fluvial deposit.

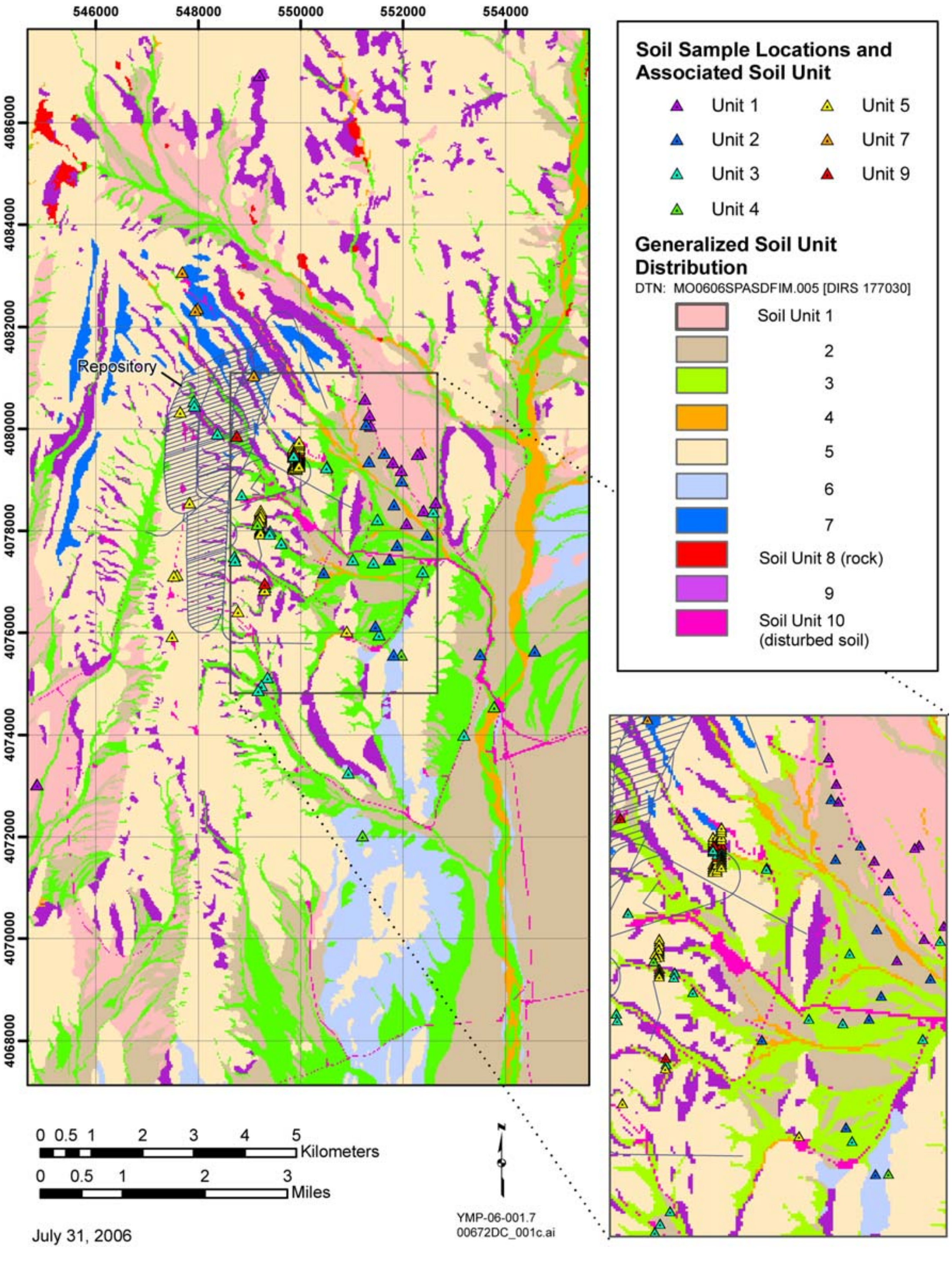
Table 6-3. Calculated Areas for Each Soil Unit

Soil Unit	Number of 30 × 30 m Cells	Calculated Area (%)
1	19,900	7.85
2	44,065	17.38
3	33,115	13.06
4	4,630	1.83
5	116,813	46.06
6	12,205	4.81
7	3,154	1.24
8	795	0.31
9	16,441	6.48
10	2,479	0.98

Source: DTN: MO0606SPASDFIM.005 [DIRS 177030].

NOTES: Total number of cells and number of cells associated with each soil unit were extracted from DTN: MO0606SPASDFIM.005 [DIRS 177030] with ARCINFO [DIRS 157019].

Total number of cells in area of interest = 253,597.



NOTES: DTN: MO0606SPASDFIM.005 [DIRS 177030] was used for map distribution of soil units. ARCINFO and ArcGIS Desktop were used to process and display geospatial data associated with soil unit distributions from DTN: MO0606SPASDFIM.005 [DIRS 177030]. DTNs: GS000383351030.001 [DIRS 148444], GS031208312211.001 [DIRS 171543], and MO0512SPASURFM.002 [DIRS 175955] were used for locations of soil samples used in this analysis.

Figure 6-1. Distribution of Soil Units, Soil Sample Locations, and Soil Units Sampled

Table 6-4. Description of Mapped Surficial Deposits and their Correlation to Soil Units Defined for Infiltration Modeling

Surficial Map Unit	Basis for Soil Unit Designation	Soil Unit (f)	USDA Descriptor (f)	Description	Soil Horizon Sequence (e)(g)	Fluvial	Eolian	Colluvium	Clay	$CaCO_3$ (h)	Desert Varnish/ Pavement	Surface Description	Comments	Sources
7	Fluvial deposits with no reportable clay or carbonate accumulation	4	Typic Torriorthents	Sandy gravel with interbedded sands	Cu	X			None	None	No soil development, no desert pavement or rock varnish	Fresh bar and swale topography, no vegetation - relatively sparse (d)	Thickness: <2 m (e). Interpreted age: late Holocene to modern. Gravel: granules to boulders; finer-grained than adjoining older units.	(a) (b) (c) (d) (e) (g)
7f		4		Same as Surficial Map Unit 7, with mafic clasts	NP	X			Same as Surficial Map Unit 7	Same as Surficial Map Unit 7	Same as Surficial Map Unit 7	Same as Surficial Map Unit 7	Same as Surficial Map Unit 7	(a) (c) (d)
6	Fluvial deposits with no to minor clay accumulation (cambic Bw - reddening, some clay structure) and Stage I to Stage II carbonate accumulation	3	Typic Haplocambids	Sandy gravel with interbedded sands. Some pedogenically mixed eolian sand in upper 30 cm (b) (c) (d)	A - Ck	X			None	Stage I (a) (b) (c) (d); Incipient, to Stage I (e)	Little-to-no soil development. Negligible rock varnish and desert pavement.	Unaltered to slightly muted (a)/ modified (b) (c) (d) bar and swale topography. Partially-to-fully vegetated.	Thickness: <2 m (e). Interpreted age: middle to late Holocene. Adjoins '7' as low (<2 m) terrace remnants. Gravel: granules to boulders	(a) (b) (c) (d) (e) (g)
6f		3		Same as Surficial Map Unit 6, with mafic clasts	NP	X			Same as Surficial Map Unit 6	Same as Surficial Map Unit 6	Same as Surficial Map Unit 6	Same as Surficial Map Unit 6	Same as Surficial Map Unit 6	(a) (c) (d)
5		3		Sandy gravel with interbedded sands. % gravel decreases upward, likely due to addition of eolian material in upper 0.5 m (b) (c) (d)	A - Bwk / Btjk - Bkq - Ck	X			Cambic Bw; Bwk, or incipient Btjk with brownish hues (10YR), weak subangular blocky structure (e)	Stage I to Stage II Stage I max (e)	Desert pavement and rock varnish very weakly developed to absent	Bar and swale topography subdued by addition of eolian sand and slopewash. More grass than older adjoining units (b) (c) (d).	Thickness: <1.5 m - overlies buried soils (d); 1 m average, 2.5 m max (e). Interpreted age: late Pleistocene to middle Holocene; <27±5 ka (e). Gravel: granules to boulders.	(a) (b) (c) (d)
5f		3		Same as Surficial Map Unit 5, with mafic clasts	NP	X			Same as Surficial Map Unit 5, with mafic clasts	Same as Surficial Map Unit 5, with mafic clasts	Same as Surficial Map Unit 5, with mafic clasts	Same as Surficial Map Unit 5, with mafic clasts	Same as Surficial Map Unit 5, with mafic clasts.	(a) (c) (d)
5s		3		Gravelly sand	NP	X			NP	Stage I	Lacks (well-packed (d)) desert pavement	Smooth surface	Interpreted age: Holocene and latest Pleistocene. Gravel: < 10 cm.	(a) (d)
4	Fluvial, with incipient to argillic clay horizon and Stage II to Stage III $CaCO_3$ development	2	Typic Haplocalcids	Sandy gravel with interbedded sands. Eolian sand and silt more abundant in upper 0.5 m (c)	Av - Btkq - Bkq - Ck	X			Incipient argillic (Btj) (a) (b) (c) (d) Btkq, with thin-to-moderately thick clay films (e)	Stage II to Stage III Stage I to Stage II (e)	Weakly to moderately varnished clasts; loosely (a) (b) (c) to moderately (tightly (e)) packed pavement	Smooth surface (b) (c)	Thickness: 1 m average; <2m (e). Interpreted age: late Pleistocene. Gravel: granules to boulders.	(a) (b) (c) (d) (e) (g)
4f		2		Same as Surficial Map Unit 4, with mafic clasts	NP	X			Same as Surficial Map Unit 4, with mafic clasts	Same as Surficial Map Unit 4, with mafic clasts	Well-packed and varnished pavement	Same as Surficial Map Unit 4, with mafic clasts	Interpreted age: late Pleistocene. On terrace ~2 m to 3 (d) m above modern wash.	(a) (c) (d)

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Table 6-4. Description of Mapped Surficial Deposits and their Correlation to Soil Units Defined for Infiltration Modeling (Continued)

Surficial Map Unit	Basis for Soil Unit Designation	Soil Unit (f)	USDA Descriptor (f)	Description	Soil Horizon Sequence (e)(g)	Fluvial	Eolian	Colluvium	Clay	$CaCO_3$ (h)	Desert Varnish/ Pavement	Surface Description	Comments	Sources
4s	Sandy fluvial deposit, with clay accumulation (up to a Bt)	2	Typic Haplocalcids	Sand and gravelly sand	NP	X			Cambic Bw to Btj	NP	Nonvarnished, darker than '5s'; loosely packed pavement	Smooth surface	Interpreted age: late Pleistocene. Gravel <10 cm.	(a) (d)
4/1	Surficial Map Unit 4 overlying Surficial Map Unit 1	2		Thin layer of Surficial Map Unit 4 partially buries Surficial Map Unit 1	NP	X			NP	NP	NP	NP	Interpreted age of Surficial Map Unit 4: late Pleistocene.	(a)
3	Fluvial deposit, with incipient to argillic clay horizon and Stage II to Stage III $CaCO_3$ development.	2		Sandy gravel with interbedded sand; percent gravel decreases upward, likely due to addition of eolian material (b) (c) (d)	Av - BA - Btkq - Kq/ Bkq - Ck	X			Reddish brown (c) (d) argillic Bt Bt, Btkq, 75 cm thick (e); clayey texture, clay films, reddish color (7.5YR) (e)	Stage II to Stage III Stage II to Stage IV (d) Stage II+– Stage III (e)	Darkly varnished, moderately (b) (c) (d) to tightly packed pavement	Smooth surface	Thickness: 2 to 2.5 m, av; >3.3 m, local. Interpreted age: middle to late Pleistocene. Gravel: granules to boulders.	(a) (b) (c) (d) (e) (g)
3f		2		Same as Surficial Map Unit 3, with mafic clasts	NP	X			Same as Surficial Map Unit 3	Same as Surficial Map Unit 3	Same as Surficial Map Unit 3	Same as Surficial Map Unit 3	Thickness: 1 to 3 m; overlies buried soils (d). Same as Surficial Map Unit 3	(a) (c) (d)
3/e	Landscape dominated by character of the underlying sandy units of eolian origin.	6	Typic Torripsamments	Thin layer of alluvium of Surficial Map Unit 3, overlying sand of Surficial Map Unit e (d).	NP	X	X		NP	NP	NP	Anomalously well dissected surface	Interpreted age: middle to late Pleistocene.	(d)
3/eo		6		Thin layer of Surficial Map Unit 3 overlying extensive sand of Surficial Map Unit eo.	NP	X	X		NP	NP	NP	Anomalously well dissected surface	Interpreted age: middle to late Pleistocene. Calico Hills source of fluvial gravel	(a)
2	Argillic B (Bt) horizon, Stage III to Stage IV $CaCO_3$ (cemented horizon).	1	Typic Argidurids	Sandy gravel with interbedded sands.	Av - Btq - Btkq - Kq - Bkq - Ck	X			Reddish brown argillic 40 to 70 cm thick, reddish (7.5-5YR) (e)	Stage III to IV (a) (b) (c) (d) Stage II to Stage III, Stage IV max Si, $CaCO_3$ (e)	Darkly varnished	Smooth surface, tightly packed pavement	Thickness: >3.5 m (e). Interpreted age: late (c) to middle (?, c) Pleistocene; middle Pleistocene (e). Gravel: granules to boulders.	(a) (c) (e) (g)
1		1		Sandy gravel with interbedded sands	Av - BA - Btkq - Kqm - Bkq - Ck	X			Argillic horizon that is either absent or partially eroded (a) (b) (c). Argillic horizon of variable thickness and expression is commonly present (d).	Stage IV, partially eroded K. K is $\geq$ 0.5m (b) (c)	Darkly varnished, with light-colored clasts of pedogenic carbonate	Well-packed pavement. Rounded ridges (ballenas) - original surface/thickness has been eroded (b) (c) (d)	Thickness: >3.3 m (e). Interpreted age: early to middle Pleistocene; overlies 0.76 Ma Bishop Ash (b) (c) (d) (e). Gravel: granules to boulders.	(a) (b) (c) (d) (e) (g)
1/e	Landscape dominated by character of the underlying sandy units	6	Typic Torripsamments	Thin layer of fluvial gravel of surficial deposit 1,overlying sandy material of Surficial Map Unit e (d).	NP	X	X		NP	NP	NP	Anomalously well dissected because of underlying sand unit	Interpreted age: early to middle Pleistocene	(d)

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Table 6-4. Description of Mapped Surficial Deposits and their Correlation to Soil Units Defined for Infiltration Modeling (Continued)

Surficial Map Unit	Basis for Soil Unit Designation	Soil Unit (f)	USDA Descriptor (f)	Description	Soil Horizon Sequence (e)(g)	Fluvial	Eolian	Colluvium	Clay	$CaCO_3$ (h)	Desert Varnish/ Pavement	Surface Description	Comments	Sources
1/eo	Landscape dominated by character of the underlying sandy units (Continued)	6	Typic Torripsamments (Continued)	Thin layer of fluvial gravel of surficial deposit 1,overlying sandy material of Surficial Map Unit eo (d).	NP	X			NP	NP	NP	Dissected surface	Interpreted age: early (?) to middle Pleistocene	(a)
0	Argillic B (Bt) horizon, Stage III to Stage IV $CaCO_3$ (cemented horizon)	1	Typic Argidurids	Lag gravel	NP	X			NP	Stage III buried soil	NP	Rounded ridges, higher than Surficial Map Unit 1 (c)	Interpreted age: late Tertiary (?)(a); middle to early Pleistocene, containing 0.76 Ma Bishop Ash (c). Small area on north end of Alice Ridge (a); along Yucca Wash and tributaries (c). Gravel: granules to boulders (c).	(a) (c)
Tgp		1		Sandy gravel	NP	X			Uniformly indurated	Stage IV, with 1 to 2 m laminar horizon	NP	Rounded dome	Thickness: 50 m, max. Interpreted age: late Miocene (early Pliocene?). Exposed only E of Fortymile Wash.	(a)
ey	Sandy material of eolian origin	6	Typic Torripsamments	Sand with 5% to 50% gravel	NP		X		Weakly developed cambic B (d)	NP	Loosely packed gravel pavement.	Undissected	Interpreted age: Holocene and late Pleistocene. Sand ramp deposits.	(a) (d)
e		6		Sand with 5% to 50% gravel	NP		X		Brown cambric to argillic B (a) (b) (c) (d). Btkq "similar to Surficial Map Unit 4" (e).	Stage II to Stage III, multiple buried calcic soils (>4)	Poorly varnished; poorly to moderately packed pavement.		Thickness: 22 m, max (a). Interpreted age: late and middle Pleistocene; overlies 0.76 Bishop Ash (d). Sand ramp deposits with substantial colluvial or sheet wash component.	(a) (d) (e) (g)
eo		6		Gravelly sand with 5% to 50% gravel	NP		X		None described	Stage IV morphology over rhizoliths			Interpreted age: middle to late Pleistocene.	(a)
cf	Colluvium with soil development and vegetated surface	9	Typic Calciargids	Colluvium and debris-flow diamictons, with interbedded alluvium and some eolian deposition	NP			X	Multiple buried soils	NP	NP	Vegetated	Thickness: 0.5 to 3 m or more (d). Interpreted age: Holocene to early Pleistocene. Gravel: granules to boulders.	(a) (b) (c) (d)
cf/e	Landscape dominated by character of the underlying sandy units	6	Typic Torripsamments	Sand-rich cobbly colluvium	NP			X	NP	NP	NP	NP	Occurs along flank of ridge west of Busted Butte.	(d)

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Table 6-4. Description of Mapped Surficial Deposits and their Correlation to Soil Units Defined for Infiltration Modeling (Continued)

Surficial Map Unit	Basis for Soil Unit Designation	Soil Unit (f)	USDA Descriptor (f)	Description	Soil Horizon Sequence (e)(g)	Fluvial	Eolian	Colluvium	Clay	$CaCO_3$ (h)	Desert Varnish/ Pavement	Surface Description	Comments	Sources
cs	Colluvium with minimal to no soil development, and minimal vegetation	5	Lithic Haplocambids	Angular gravel; Silt and sand content increases with depth	NP			X	Silt and sand under surface increases with depth	NP	Varnish ranges from dark to absent	Poorly vegetated	Interpreted age: Pleistocene; varnish dated as 0.8 Ma. Gravel: pebbles to boulders.	(a) (b) (c) (d)
cu	Colluvium, undivided	5	Lithic Haplocambids	Diamicton with gravel clasts and an eolian matrix	NP			X	NP	NP	NP	NP	Thickness: <1 m. Interpreted age: Quaternary; surface characteristics of units 5 and 6 (e). Includes common small bedrock outcrops. Thin mantle, some eolian fine-grain input.	(a) (b) (c) (d)
rc	Colluvium with argillic clay matrix and large bedrock slabs	7	Lithic Haplargids	Diamicton composed of tabular slabs of caprock	NP			X	Reddish brown, sandy clay loam matrix	NP	Variable varnish development. Loosely to tightly packed pavement.	NP	Thickness: <1m (b), (c). Residuum.	(a) (b) (c)
d	Disturbed surface	10	Disturbed ground	Compacted surficial or imported materials	NA	NA	NA	NA	NA	NA	NA	NA	Interpreted age: Historic. Disturbed areas.	(a) (b) (c) (d)
r	Bedrock	8	Rock	Volcanic bedrock of Tertiary age.	NA	NA	NA	NA	NA	NA	NA	NA	Interpreted age: Miocene. Volcanic bedrock.	(a) (c) (d)

NOTES: Letters in parentheses refer to the following sources:

(a) DTN: GS940108315142.004 [DIRS 160344].

(b) DTN: GS940708315142.008 [DIRS 160346].

(c) DTN: GS940108315142.005 [DIRS 160345].

(d) DTN: GS950408315142.004 [DIRS 160347].

(e) Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

(f) DTN: GS960408312212.005 [DIRS 146299], Data Summary Sheet.

(g) Surficial Map Unit 7 is the equivalent to unit Qa7 by Keefer et al. (2004 [DIRS 173899], Chapter 2); similarly, Surficial Map Unit 6 = Qa6, Surficial Map Unit 5 = Qa5, Surficial Map Unit 4 = Qa4, Surficial Map Unit 3 = Qa3, Surficial Map Unit 2 = Qa2, Surficial Map Unit 1 = Qa1, and Surficial Map Unit 0 = QT0.

(h) Carbonate stages (in gravel sediments): Stage I: thin, discontinuous coatings, sparse to common, usually on underside of pebbles (maximum carbonate percent in <2mm fraction = 2%); Stage II: continuous, thin to thick coatings on tops and undersides of pebbles; some carbonate in matrix (2% to 10% $CaCO_3$); Stage III: massive accumulations between clasts, essentially continuous dispersion in matrix (K fabric), becomes cemented in advanced form (10% to 25% $CaCO_3$); Stage IV: thin (<0.2 cm) to moderately thick (1 cm) laminae in upper part of cemented K horizon, which is 0.5 to 1 m thick; cemented platy to weak tabular structure and indurated laminae (>25% $CaCO_3$ in deposits having >50% gravel) (Machette1985 [DIRS 104660]).

The primary source for the table is (a) unless otherwise designated, entries in the column labeled "Sources" identify which of the above sources discuss a particular unit. References to sources elsewhere in the table pertain to specific information from that source.

Abbreviations for soil horizon sequences: Soil horizons A, B, C, K: A, surface soil horizon characterized by accumulation of organic matter, typically as a zone of illuviation of clay, sesquioxides, silica, gypsum, carbonate, and (or) salts; B, subsurface soil horizon characterized by reddening, stronger development and (or) accumulation of secondary illuvial materials (clay, sesquioxides, silica, gypsum, and salts); C, subsurface soil horizon that may appear similar or dissimilar to parent material and that includes unaltered material and material in various stages of weathering; K, subsurface soil horizon engulfed with carbonate to the extent that its morphology is determined by the carbonate. Master horizon modifiers: j, used in conjunction with other modifiers to denote incipient development of that particular soil characteristic; k, accumulation of carbonate; m, strong cementation; q, accumulation of silica; t, accumulation of clay; v, vesicularity; w, color or structural B soil horizon (Keefer et al. 2004 [DIRS 173899], Table 3).

NA = Not applicable; NP = Information not provided; USDA = U.S. Department of Agriculture.

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6.2.3 Verification of Soil Unit Designation

6.2.3.1 Approach

DTN: GS960408312212.005 [DIRS 146299] establishes the grouping of the surficial map units into soil units to be used as input to an infiltration model. The approach used is based on the classification of soils established by the USDA (1999 [DIRS 175948], Chapters 11 and 12). Use of USDA soil taxonomy to establish groupings of surficial deposits for use in an infiltration model is reasonable because:

- USDA taxonomy is a rigorous methodology of grouping soils of similar characteristics with specific quantitative criteria for classification that is used throughout the United States and elsewhere in the world.

- Infiltration modeling is most concerned with the near surface character of surficial deposits, such as particle size distribution, because infiltration processes are concentrated near-surface in an arid environment, such as that at Yucca Mountain. Soil development also occurs primarily in the uppermost meter of the deposits, and the pedogenic changes to the soil profile affect the particle size distribution of the deposits. The soil taxonomy system captures the particle size variations, as well as the moisture regime and pedogenic changes that occur through time.

Thus, a taxonomy that is descriptive of the uppermost 1 to 3 m of the surface materials is appropriate to classify those materials for an infiltration model.

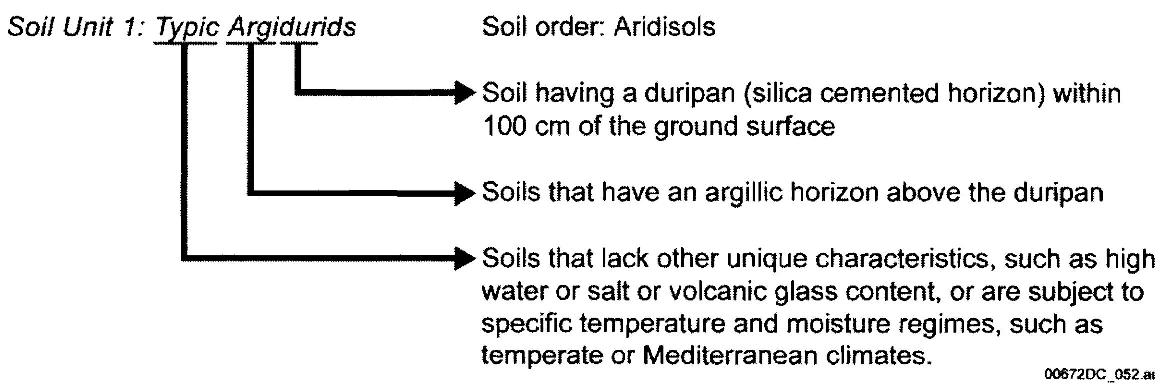
The key factors for applying the soil taxonomic principles to the infiltration groupings are the amount of clay accumulation in the deposits, the extent of pedogenic calcium carbonate accumulated in the deposits, and the variation in the particle size distribution. The grouping defined in DTN: GS960408312212.005 [DIRS 146299] uses these pedogenic characteristics, which effectively reflect the age of a deposit. This approach for defining soil units applicable to an infiltration model is corroborated by "Hydraulic Properties of a Desert Soil Chronosequence in the Mojave Desert, USA" (Young et al. 2004 [DIRS 176416]), which demonstrates that infiltration properties are directly related to the age of surficial deposits, and by "The High Water Holding Capacity of Petrocalcic Horizons" (Duniway et al. 2004 [DIRS 176417]), which demonstrates that the buildup of pedogenic carbonate in a soil increases the water holding capability of the soil. Thus, this evaluation concludes that the grouping approach used in DTN: GS960408312212.005 [DIRS 146299] was appropriate in developing input for an infiltration model.

6.2.3.2 Soil Unit Definition

The highest level of the systematic USDA soil classification is the soil order. A soils map of the United States shows that only three of 12 soil orders are mapped in southern Nevada: aridisols, entisols, and mollisols (USDA 1999 [DIRS 175948], map Dominant Soil Orders). The other nine soil orders reflect one or more of the following: higher rainfall, colder soils, higher organic carbon, extreme weathering of minerals, or higher clay content than soils observed at Yucca Mountain. Mollisols occur in isolated areas of southern Nevada; generally, these soils are characterized by a relatively thick, dark-colored, humus-rich surface horizon, such as the soils common to grasslands. These soils do not reflect the soils observed at Yucca Mountain and are, thus, considered not applicable to the infiltration classification. The presence of only aridisols and entisols at Yucca Mountain has also been reported in *Soil Survey of Yucca Mountain Study Area, Nye County, Nevada* (Resource Concepts 1989 [DIRS 103450]), hereafter referred to as the 1989 soil survey.

Aridisols are soils that do not have water available to mesophytic plants, which are plants that grow under medium conditions of moisture for long periods. The central concept of entisols is that there is little or no evidence of the development of pedogenic horizons, because the deposits are too young for soils to have begun forming; or new material is introduced each year; or the soils are on steep, actively eroding slopes; or the deposits consist of minerals, such as quartz, that do not degrade to form soil horizons. Entisols may overlie buried soils that are greater than 1 m in depth and that demonstrate either clay or carbonate accumulation (USDA 1999 [DIRS 175948], Chapters 11 and 12).

The descriptions of soil survey nomenclature (USDA 2003 [DIRS 175947], Chapters 7 and 8), assigned to infiltration model units, demonstrate the character of the units and basis for unit definition (Figures 6-2 to 6-9). Unless indicated otherwise, descriptions of mapped surficial deposits are from Keefer et al. (2004 [DIRS 173899], Chapter 2) and from Swan et al. (2001 [DIRS 158784], pp. 8 to 21). These descriptions verify that the grouping of surficial map units into soil units by DTN: GS960408312212.005 [DIRS 146299] is appropriate, and they provide the rationale for the grouping.



Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-2. Description of Soil Unit 1: Typic Argidurids

Surficial Map Units 0, 1, 2, and Tgp, which have been grouped into Soil Unit 1 (Table 6-2), are the oldest Quaternary deposits that have been mapped in the Yucca Mountain area and are interpreted to be fluvial deposits of early to middle Pleistocene age. Their age is indicated by the extent of accumulation of silica and carbonate in the soil horizons, which have become cemented and effectively limit downward migration of infiltrating water, and by a well-packed desert pavement on the surface (Table 6-4). As portrayed in Figure 6-1, Soil Unit 1 encompasses 8% of the mapped area (Table 6-3).

Soil Unit 2: Typic Haplocalcids — Soil order: Aridisols

- *Calcids*: Soil having a calcic horizon within 100 cm of the ground surface
- *Haplo*: The calcic horizon is not cemented
- *Typic*: Soils that lack other unique characteristics, such as high water or salt or volcanic glass content, or are subject to specific temperature and moisture regimes, such as temperate or Mediterranean climates.

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Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-3. Description of Soil Unit 2: Typic Haplocalcids

Soil Unit 2 consists of fluvial deposits of Surficial Map Units 3 and 4, which exhibit some argillic (clay) accumulation, as well as noticeable carbonate accumulation (Table 6-4). Although the carbonate may be sufficient to almost encompass the horizon, it has not developed a cemented character. The desert pavement developed on the surface of these deposits is moderately-to-tightly packed. Eolian deposits, consisting of a sandy, silty material, have accumulated in the upper 0.5 m underneath the pavement and above the parent fluvial deposits. Soil Unit 2 comprises about 17% of the infiltration model area (Table 6-3) and includes Surficial Map Units 3 and 4 (Table 6-2), and subunits thereof, which are considered to be of middle to late Pleistocene age (Keefer et al. 2004 [DIRS 173899], Table 2).

Soil Unit 3: Typic Haplocambids — Soil order: Aridisols

- *Cambids*: The soil does not have a salic, gypsic, argillic, calcic, or petrocalcic horizon within 100 cm of the ground surface
- *Haplo*: The soil is not irrigated, saturated, or anthropologically modified and does not have a cemented horizon within 150 cm of the ground surface
- *Typic*: Soils that lack other unique characteristics, such as high water or salt or volcanic glass content, or are subject to specific temperature and moisture regimes, such as temperate or Mediterranean climates.

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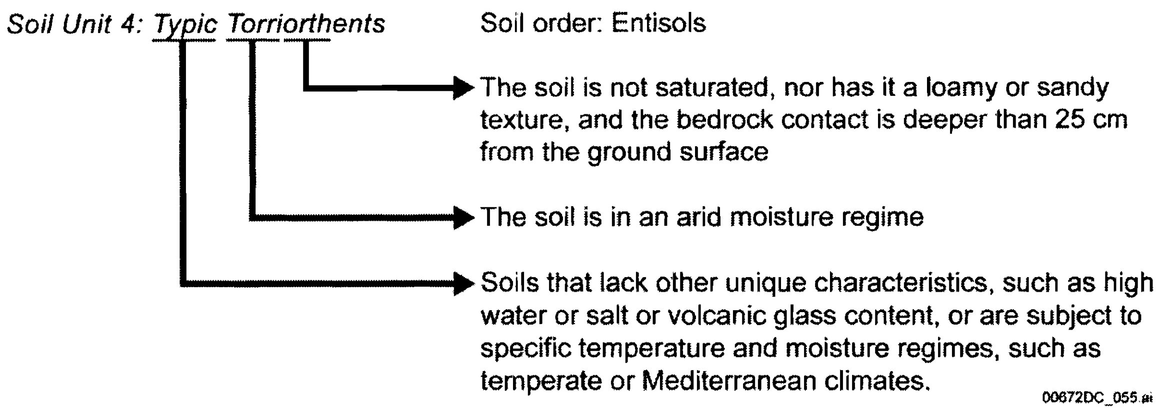
Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-4. Description of Soil Unit 3: Typic Haplocambids

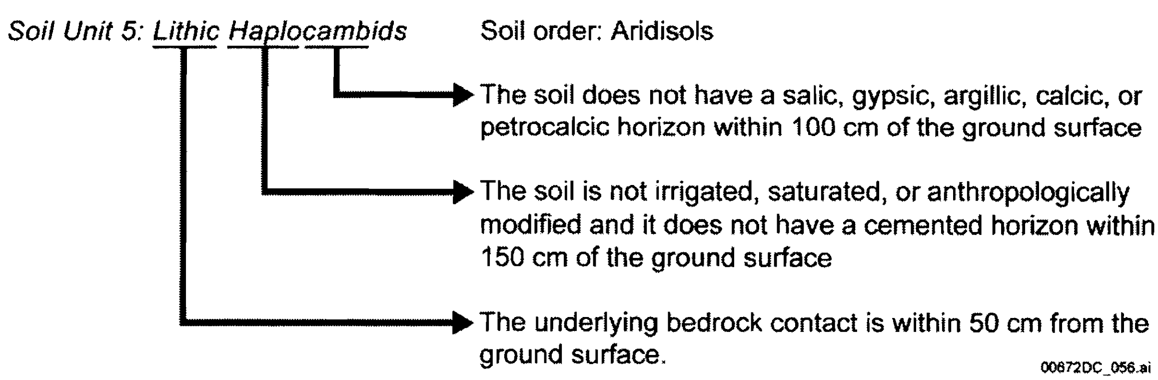
Fluvial deposits of Surficial Map Units 5 and 6, which constitute Soil Unit 3, have no to minor clay accumulation, and visible but minor carbonate accumulation in the soil horizons (Table 6-4). Desert pavement is not present or is weakly developed where present on these deposits. The addition of some eolian material is evident in the upper 30 cm of the deposits. This deposit covers about 13% of the model area (Table 6-3) and comprises Surficial Map Units 5 and 6 (Table 6-2), and subunits thereof, which are considered to be of latest Pleistocene to middle to late Holocene age (Keefer et al. 2004 [DIRS 173899], Table 2).



Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-5. Description of Soil Unit 4: Typic Torriorthents

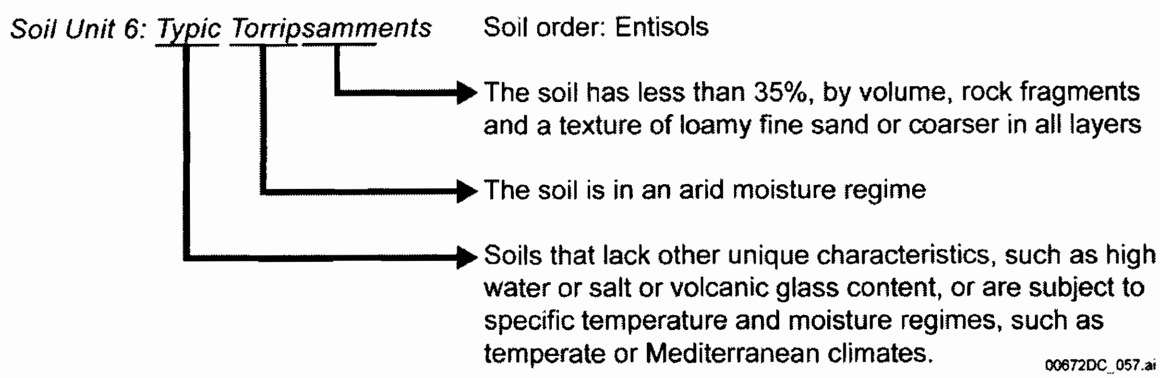
The most characteristic feature of Surficial Map Units 6 and 7, which are grouped into Soil Unit 4, is the apparent lack of soil development of clay, or of carbonate accumulation, in any horizon and the recent appearance of these fluvial deposits (Table 6-4). They are confined to the modern stream channels (Surficial Map Unit 7) and are subject to reworking in runoff events. The deposits have not been stable for a sufficient time for desert pavement to develop and are found over less than 2% of the infiltration model area (Table 6-3).



Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-6. Description of Soil Unit 5: Lithic Haplocambids

Soil Unit 5 is the most extensive of the model units, covering 46% of the infiltration model area (Table 6-3), and is comprised of colluvial and debris flow deposits that mantle the hill slopes throughout the Yucca Mountain area (Table 6-4, Surficial Map Units cu and cs). This colluvial unit is typified by a thin mantle of angular rock rubble having lithologies of the underlying bedrock. The colluvium is generally less than 1 m in thickness. The clast-supported deposit lacks fine-grained material at the surface, but silt and sand of inferred eolian origin occur beneath the surface and increase with depth. The unit is poorly vegetated and occurs in various hill slope positions. Some deposits are estimated to be of early to mid-Pleistocene age, based on desert varnish development on rock clasts.



Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-7. Description of Soil Unit 6: Typic Torripsamments

The mapped eolian deposits, e, eo, ey, 1/ eo, 3/eo, and cf/e, are included in Soil Unit 6 (Table 6-2), which represents about 5% of the mapped area (Table 6-3). The most prominent units are the sand ramps that are preserved on the flanks of bedrock highs, such as Busted Butte. Some deposits are up to 22 m thick and exhibit multiple buried soil horizons, suggesting an episodic depositional history. The description of the sand ramps is from DTN: GS940108315142.004 [DIRS 160344], p. 11 of 13. The unit is primarily gravelly sand, with 5% to 50% gravel; soil development is evidenced by argillic and carbonate horizons. The angular gravel observed in exposures is interpreted to indicate substantial colluvial and possibly sheetwash processes during deposition.

Soil Unit 7: Lithic Haplargids Soil order: Aridisols

- The soil has an argillic horizon, and does not have a petrocalcic horizon, within 100 cm of the soil surface
- The soil does not have a cemented, gypsic, or calcic horizon or a paleosol within 150 cm of the ground surface
- The underlying bedrock contact is within 50 cm from the ground surface.

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Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-8. Description of Soil Unit 7: Lithic Haplargids

Soil Unit 7 occurs in about 1% of the map area (Table 6-3) and is confined to vegetated ridgetops in the northernmost part of the infiltration model area (Figure 6-1; Table 6-4, Surficial Map Unit rc). It is a thin mantle, generally less than 1 m thick, of an angular gravel diamicton composed of tabular slabs of the underlying Tiva Canyon bedrock mixed with a sandy clay loam soil matrix. The fine-grained matrix is attributed to an eolian origin. A tightly packed desert pavement has developed on the relatively level surfaces (DTN: GS940108315142.005 [DIRS 160345]).

Soil Unit 8: Bedrock

Soil Unit 8 comprises 0.3% of the map area (Table 6-3) and defines exposed bedrock (Table 6-2). Hydraulic properties for exposed bedrock are developed in *Data Analysis for Infiltration Modeling: Bedrock Saturated Hydraulic Conductivity Calculation* (BSC 2006 [DIRS 176355]) and are not discussed further in this analysis.

Soil Unit 9: Typic Calciargids Soil order: Aridisols

- The soil has an argillic horizon, and does not have a petrocalcic horizon, within 100 cm of the soil surface
- The soil has a calcic horizon that has its upper boundary within150 cm of the soil surface
- Soils that lack other unique characteristics, such as high water or salt or volcanic glass content, or are subject to specific temperature and moisture regimes, such as temperate or Mediterranean climates.

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Sources: Keefer et al. 2004 [DIRS 173899], Chapter 2; Swan et al. 2001 [DIRS 158784], pp. 8 to 21.

Figure 6-9. Description of Soil Unit 9: Typic Calciargids

Vegetated colluvial deposits at the toes of hillsides have been grouped into Soil Unit 9 (Table 6-2). This unit defines about 6% of the model area (Table 6-3) and consists of interbedded colluvium and debris flow deposits, grading to and interbedded with alluvium on upper fan surfaces (Table 4, Surficial Map Unit cf). Reported thickness ranges from 0.5 to 3 m and the extent of soil development observed is comparable to that of Soil Units 3 and 4.

Soil Unit 10: Disturbed Ground

Soil Unit 10 comprises 1% of the map area (Table 6-3) and defines disturbed ground (Table 6-2) such as roads, drilling pads, and construction areas. As shown in Figure 6-1, most of the disturbed soils (Soil Unit 10) are associated with Soil Units 1, 2, and 3. The hydraulic properties assigned to Soil Unit 10 are properties of the soils from which they are derived (Section 6.3) and vary by location depending on the underlying soil unit. No properties unique to Soil Unit 10 were developed in this analysis.

6.2.4 Corroboration with Other Soil Surveys

Two other soil surveys have been completed for portions of the Yucca Mountain infiltration model area. In a 1989 soil survey, the distribution of four soil units was shown at a small scale for Yucca Mountain (Resource Concepts 1989 [DIRS 103450], Figure 2). In 2004, a soil survey for the southwestern portion of Nye County was published (USDA 2004 [DIRS 173916]), hereafter referred to as the 2004 soil survey. The Busted Butte quadrangle of this survey covers the southwest portion of Yucca Mountain, which is administered by the Bureau of Land Management. The 2004 soil survey did not map the two-thirds of the Yucca Mountain infiltration model area that is administered by Nellis Air Force Base or has been set-aside for the Nevada Test Site. The mapping of soil units in the 1989 and 2004 soil surveys (Resource Concepts 1989 [DIRS 103450]; USDA 2004 [DIRS 173916]) are compared with the mapping of soil units in DTN: GS960408312212.005 [DIRS 146299] (Figure 6-1), as shown in Figure 6-10.

The approach used by these two alternative soil surveys is equivalent to that used by DTN: GS960408312212.005 [DIRS 146299] in that the soils are identified by USDA taxonomic nomenclature and are, thus, subdivided by characteristics such as depth to bedrock, the presence or lack thereof of a duripan with depth, or observable pedogenic products. Soil series distribution, USDA taxonomic names, and equivalent soil units identified herein are listed in Table 6-5. Some of the taxonomic names used in the 1989 soil survey (Resources Concepts 1989 [DIRS 103450]) predate the more recent nomenclature used in DTN: GS960408312212.005 [DIRS 146299] and in the 2004 soil survey (USDA 2004 [DIRS 173916]); Table 6-5 provides equivalent names.

In general, the mapping of soil units shown in Figure 6-1 is more detailed than shown in other surveys. Also, the soil units used in the 2004 soil survey (USDA 2004 [DIRS 173916]) were applied to a much larger geographical area than just Yucca Mountain and, thus, may represent a characterization that accommodates a wider range of features than those observed in the infiltration model area. For example, one of the most common soil types is described as developed in lacustrine deposits, which do not occur in the infiltration model area, but do occur further to the west in the Amargosa Valley area.

A visual comparison was made by overlaying the two surveys over the Yucca Mountain soils map (Figure 6-1). The overlap between the 2004 soil survey (USDA 2004 [DIRS 173916]) and the 1989 soil survey (Resources Concepts 1989 [DIRS 103450]) is minimal and is limited to an east-west swath about 2,000 ft wide at the northernmost portion of the soils map (Figure 6-1) of Yucca Mountain. The soil unit taxonomic identifications are summarized in Table 6-5. Some of the differences in the taxonomic naming indicated in Table 6-5 reflect an interpretation of the age of the surficial deposits. The most divergent example is Soil Unit 3 of the 1989 soil survey (Resources Concepts 1989 [DIRS 103450]), which is characterized by a soil having a duripan, or a petrocalcic horizon. Their map area includes areas mapped in DTN: GS940108315142.004 [DIRS 160344] as having a petrocalcic soil (grouped into Soil Unit 1), as well as areas of fluvial deposits that do not have a petrocalcic horizon and, thus, were interpreted to be much younger in age (Soil Units 3, 4, and 5).

Another possible explanation for the differences between the soil survey shown in Figure 6-1, the 1989 soil survey (Resources Concepts 1989 [DIRS 103450]), and the 2004 soil survey (USDA 2004 [DIRS 173916]), is that the two latter surveys apply soil series identified elsewhere in the county or region to the soils observed at Yucca Mountain. The soils identified on Figure 6-1, on the other hand, were mapped and observed strictly within the area of Yucca Mountain, and the characteristics observed were developed in a limited microclimate and on more homogeneous parent material than the soil series that are applied across the whole of Nye County or the region.

Overall, the 1989 soil survey (Resources Concepts 1989 [DIRS 103450]) and the 2004 soil survey (USDA 2004 [DIRS 173916]) corroborate the Yucca Mountain soil mapping (BSC 2004 [DIRS 170007]) used for input to an infiltration model with regard to approach and definition of units; the following conclusions summarize the comparison:

- All three soil surveys–mapping identify soils on only two soil groups: the aridosols and the entisols.

- The geographic extent of Soil Unit 5, which encompasses 46% of the infiltration model area (Table 6-3), is generally also defined in the 1989 and 2004 soil surveys with respect to the portions of Yucca Mountain covered by those surveys.

- Similarly, the boundaries of other soil classifications in the 1989 and 2004 soil surveys are in general agreement with boundaries of the Yucca Mountain soil units.

- The range of soil types identified by all three soil surveys–mapping is defined by relative occurrences of argillic, petrocalcic (or duripan), or calcic horizons, or little to no soil development.

- The most consistent agreement with regard to soil taxonomic naming of units is for those soils that have little to no pedogenic soil development.

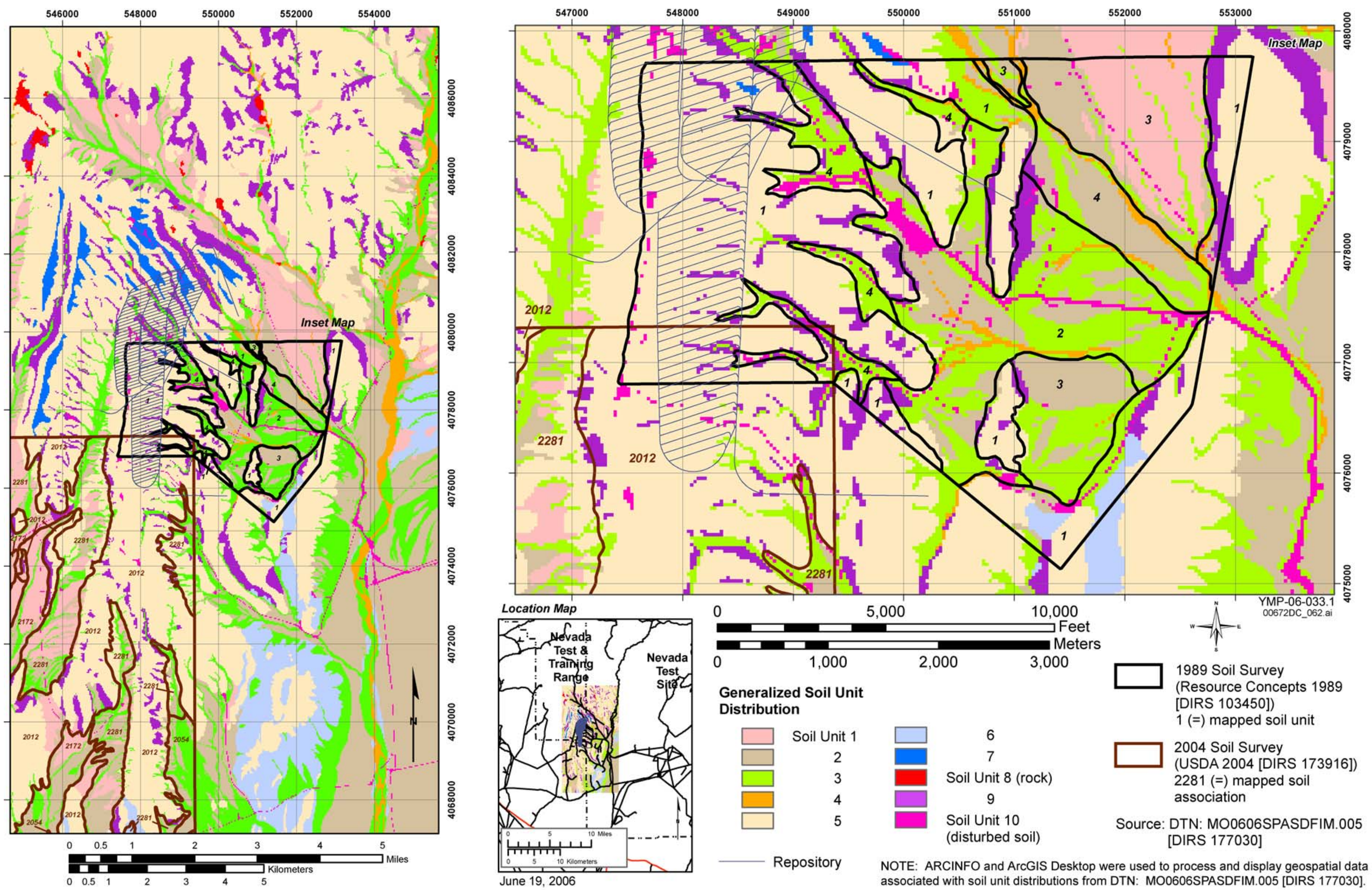

Figure 6-10. Generalized Soil Unit Distribution

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Table 6-5. Comparison of Taxonomic Nomenclature for Soil Surveys

Source Designation	Depth to Bedrock (cm)	Duripan within 100 cm	Argillic over Duripan	No Argillic or Salt Horizon over Duripan	Calcic Horizon	Argillic over Calcic Horizon	Argillic Horizon	Little Pedogenic Soil Development	Has Durinodes
1989 Soil Survey[a]									
Soil Unit 1	<50		LDar	LDor			LH SU7	LT SU 5[c]	
	<100								
	<150					SU 9			
Soil Unit 2	<50								
	<100		Dar	TDor	SU 2[c]			SU 3[c]	
	<150					SU 9			
Soil Unit 3	<50		TDar	TDor					
	<100		SU 1[c]		SU 2			SU 3	
	<150								
Soil Unit 4	<50								
	<100				SU 2	THar		TT SU 3[c]	
	<150								
2004 Soil Survey[b]									
2012 Soil Association 309 = 3, 285 = G 336 = U	<50							LT SU 5[c]	
	<100	TH				SU 9			
	<150								
2054 Soil Association Y = 347 A = 259	<50								
	<100				SU 2[c]			TT SU 3[c]	
	<150								
2172 Soil Association S = 315 Y = 347	<50								
	<100		SU 1		SU 2[c]			TT	DT
	<150								
2281 Soil Association S = 322 Y = 347	<50								
	<100	TH	SU 1		SU 2[c]			TT SU 3	
	<150								

NOTES: DT = Duric Torriorthents; LDar, Lithic Durargids = Lithic Haplargids; LDor, Lithic Durothids = Lithic Haplodurids; LH, Lithic Haplargids; LT, Lithic Torriorthents; TDar, Typic Durargids = Typic Haplargids; TDor, Typic Durorthids = Typic Haplodurids; TH, Typic Haplodurids; THar, Typic Haplargids; TT, Typic Torriorthents.

SU 1 = Soil Unit 1, Typic Argidurids; SU 2 = Soil Unit 2, Typic Haplocalcids; SU 3 = Soil Unit 3, Typic Haplocambids; SU 4 = Soil Unit 4, Typic Torriorthents; SU 5 = Soil Unit 5, Lithic Haplocambids; SU 7 = Soil Unit 7, Lithic Haplargids; SU 9 = Soil Unit 9, Typic Calciargids.

[a] Resources Concepts 1989 [DIRS 103450], Table 1 and Figure 2.

[b] USDA 2004 [DIRS 173916], pp. v, vi, 259, 285, 315, 322, 336, 347, and 349.

[c] Primary soil units for geographic areas (Section 6.2.3.2) are from DTN: MO0606SPASDFIM.005 [DIRS 177030].

The differences in assigned taxonomic names (Table 6-5) are not great. Because the development of the hydraulic parameters to be used in an infiltration model is dependent on laboratory analyses of soil samples of a soil unit (Section 6.3), the taxonomic name assigned to a soil unit does not influence subsequent analyses, whereas the areal extent of the unit does have an influence with regard to input to an infiltration model. The 1989 soil survey (Resources Concepts 1989 [DIRS 103450]) and the 2004 soil survey (USDA 2004 [DIRS 173916]) corroborate the methodology of defining the extent of units, particularly that of Soil Unit 5, which is the most extensive of the soil units used in the infiltration model (BSC 2004 [DIRS 170007]).

6.2.5 Alternative Approach for Definition of Soil Units

Two alternative approaches for defining soil units for infiltration modeling are considered. One approach is to further subdivide the soil units by assigning unique hydraulic properties to each of approximately 40 surficial deposits map units and, therefore, have approximately 40 soil units in an infiltration model. As indicated in Table 6-2, more than 25 of the 40 surficial map units represent fluvial deposits; descriptions of these units (DTNs: GS940108315142.004 [DIRS 160344], Busted Butte northeast; GS940108315142.005 [DIRS 160345], Topopah Spring south; GS940708315142.008 [DIRS 160346], Busted Butte northwest; and GS950408315142.004 [DIRS 160347], Busted Butte south) indicate that they are similar with regard to observable particle size distribution and depositional character.

These units were differentiated by the extent of accumulation of pedogenic products in the fluvial deposit, such as the accumulation of clay and calcium carbonate, which is a function of the age of the deposit. Because age dating of every deposit by laboratory methods to get an "exact" age is both labor and time intensive, surficial deposits have been defined as falling within relative ranges of ages based on pedogenic changes that have occurred, as well as other criteria, such as topographic position above the present stream channels. In addition, as discussed further on, only a limited number of the 40 map units have laboratory data that could be used in the assignment of hydraulic parameter values. Therefore, no further consideration is given to this approach.

The second approach is to further combine soil units. The soil units have already been combined into 10 groups from 40 surficial deposit map units. This group, referred to as the "base case" group, is based on depositional character and relative age resulting in a reduction from 40 to 10 soil units to be used as input to an infiltration model. Ten soil units are appropriate based on depositional characters and relative age. Because there is only one sample for Soil Unit 6, which has the texture of sand (DTN: GS940108315142.004 [DIRS 160344]), it is not possible to state that this sample is representative of the complete unit and, thus, direct statistical analysis of this unit is precluded (Section 6.3). Soil Unit 6 is described as primarily gravelly sand with 5% to 50% gravel and soil development evidenced by argillic and carbonate horizons (Section 6.2.3.2).

Surficial map units of Soil Unit 2 are described as (Table 6-4): sand and gravelly sand, sandy gravel with interbedded sands, eolian sand and silt more abundant in the upper 0.5 m, and sandy gravel. These descriptions are sufficiently similar to allow for the assumption that the hydraulic properties of Soil Unit 6 would be the same as those of Soil Unit 2. The effect associated with this assumption is small because Soil Unit 6 comprises less than 5% of the soils in the infiltration model area (Table 6-3). The closest occurrence of Soil Unit 6 is approximately 1.5 mi east of the lower extent of the projected repository footprint (Figure 6-1) and there are no occurrences of Soil Unit 6 over the projected repository footprint.

Soil Unit 8 is described as bedrock (Table 6-2), therefore, soil hydraulic parameters are not defined in Section 6.3. Soil Unit 10 consists of disturbed soils, which cover less than 1% of the infiltration model area (Table 6-3). There are no samples of disturbed soil, therefore, the hydraulic properties for Soil Unit 10 are assumed to be those of the adjacent soil.

The soil groups are further combined to assess the sensitivity on hydraulic property values on grouping. The first alternative grouping reduces the number of soil units to four, considering the characteristics of the soil units previously described and the number of Yucca Mountain samples in each of the base case soil units. The alternative grouping of four soil units is initially divided between fluvial and colluvial depositions.

Base case Soil Units 1 and 2 are fluvial deposits and each unit has a sufficient number of Yucca Mountain soil samples to be considered separately. Soil Unit 6 is the only soil classified as an eolian deposit (Table 6-4) and, as previously discussed, is similar to Soil Unit 2. Thus, Soil Unit 6 is grouped with Soil Unit 2 and is called Soil Unit 2-6. Soil Units 3 and 4 are also fluvial deposits and are combined into one group called Soil Unit 3-4 based on their apparent textural similarities. Soil Units 5, 7, and 9 are colluvial deposits and are combined into one group called Soil Unit 5-7-9, also based on their apparent textural similarities.

To further assess the sensitivity of hydraulic property values on grouping, a second alternative grouping, consisting of all Yucca Mountain soils in one group, is considered. This group consists of fluvial, colluvial, and eolian soil deposits.

In Section 6.3, soil hydraulic parameters and associated statistics are first developed and evaluated for the base case Soil Units 1 to 5, as well as 6 (assumed to have the same properties as Soil Unit 2), and 7 and 9. Statistics for two alternative soil groupings are then developed.

6.3 DEVELOPMENT OF SOIL HYDRAULIC PARAMETERS

The discussion of soil hydraulic parameters in Sections 6.3.1 through 6.3.3 apply equally to all soil groupings. The hydraulic parameter values developed as input to an infiltration model are:

- Saturated hydraulic conductivity, K_{sat}
- FC, which is defined as the moisture content at –0.33 bar and –0.10 bar
- PWP, which is defined as the moisture content at –60 bar
- Saturated moisture content, θ_s
- WHC, which is defined as difference between the FC and PWP (for alternate soil groups 1 and 2 only).

Statistics associated with these parameters are also developed to support stochastic analysis of infiltration. Statistics are developed for each soil group to assess the sensitivity of the grouping soils. A pedotransfer function (PTF) approach is used to develop soil hydraulic parameters needed for infiltration modeling because site-specific soil texture data are available but site-specific measurements of the hydraulic parameters K_{sat}, FC, PWP, and θ_s are not available. There are at least three general approaches that have been used to develop PTFs (Nemes et al. [DIRS 177511], p. 327). Two of the approaches are parametric approaches that rely on equations with parameters found from fitting those equations to data. Examples are regression techniques such as those used by Brakensiek and Rawls (1994 [DIRS 175944]) and artificial neural networks such as those developed for the USDA program ROSETTA (Schaap et al. 2001 [DIRS 176006]). Parametric approaches have drawbacks that include identifying the correct equation and determining that the probability distributions of errors are similar across the data space (Nemes et al. [DIRS 177511], p. 327). The approach used herein is a nonparametric approach. A nonparametric approach can be beneficial when the form of the relationship between the inputs and outputs in not known in advance, such as is the case with soil hydraulic properties (Nemes et al. [DIRS 177511], p. 327).

Soil hydraulic parameter values from the analogous site have been determined and cataloged in a database, along with soil texture information that allow for matching Yucca Mountain soil texture to the soil texture in the analogous site database. This is a type of nonparametric pedotransfer function (Sections 6.3.1 and 6.3.2). In the analogous site database, K_{sat} was determined using a constant head permeameter apparatus (Khaleel and Freeman 1995 [DIRS 175734], Section 2.0) on the less than 2 mm size fraction of the collected sample. The K_{sat} value was adjusted for gravel content, if gravel was present (Khaleel and Freeman 1995 [DIRS 175734], Appendix A and Section 3.2).

The parameters FC, PWP, and θ_s were determined from the moisture retention curves (MRCs) provided in the analogous database (Khaleel and Freeman 1995 [DIRS 175734], Appendix B). The MRCs were developed by fitting the van Genuchten soil-moisture retention model to the laboratory data, adjusted for gravel content if necessary (Khaleel and Freeman 1995 [DIRS 175734], p. iii). FC and PWP are determined from these MRCs by scaling the appropriate moisture content from the MRC at selected matrix potentials.

Field capacity has been defined as the soil moisture content at which internal drainage ceases based on observations that the rate of flow and water-content changes decrease with time after a precipitation or irrigation event (Hillel 1980 [DIRS 100583], p. 67). This concept, however, was recognized as arbitrary and not an intrinsic soil property independent of the way it is measured (Hillel 1980 [DIRS 100583], p. 68). For the development of inputs to an infiltration model, FC values based on both matric potentials of –0.33 bar and –0.10 bar are developed to capture the uncertainty inherent with the FC concept (Section 5.3).

Values for PWP were determined at a soil water potential of –60 bar, from MRCs in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendix B). This is consistent with the lower limits of soil moisture extraction determined for several Mojave Desert shrubs that can survive soil water potentials as low as –50 to –100 bar (Bamburg et al. 1975 [DIRS 127392], Figures 1 and 2; Hamerlynck et al. 2000 [DIRS 177022], Figure 3; Hamerlynck et al. 2002 [DIRS 177046], Figure 6; Odening et al. 1974 [DIRS 177026], pp. 1089 to 1090; Smith et al. 1997 [DIRS 103636], pp. 95, 110, 115 and 116).

The θ_s parameter is a van Genuchten parameter (van Genuchten et al. 1991 [DIRS 108810]) and is tabulated in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendix A).

The hydraulic parameter values for the Yucca Mountain soil units are developed by matching grain-size distributions of Yucca Mountain samples, from laboratory analysis, to grain-size distributions from soil samples in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B), similar to the approach used by the DOE to evaluate fate and transport of high-level radioactive waste from large nominal one-million gallon subsurface tanks (JE 1999 [DIRS 176154], Section B.1.1.2).

The fraction of sand, silt, and clay in a soil can be an effective predictor of hydraulic parameter values. For instance, the USDA Salinity Laboratory has developed an automated approach that matches the fraction of sand, silt, and clay in a soil to the soils in their database, and then outputs the associated hydraulic parameter values. Two other alternative PTF approaches were used as for corroboration (Section 6.4).

One approach considered was ROSETTA and its associated database. The ROSETTA program database contains 2,134 samples for water retention, 1,306 samples for K_{sat}, and 235 samples for unsaturated hydraulic conductivity. Samples were obtained from a large number of sources that involve agricultural and non-agricultural soils in temperate climate zones of the northern hemisphere, mainly from the United States of America and some from Europe. The advantages of ROSETTA include its ease of use, its highly respected developers, and it was developed by the USDA.

Another approach considered was documented in "Developing Joint Probability Distributions of Soil Water Retention Characteristics" (Carsel and Parrish 1988 [DIRS 147295]) and in "Prediction of Soil Water Properties for Hydrologic Modeling" (Rawls and Brakensiek 1985 [DIRS 177045]). Joint multivariate density functions were developed for various USDA textural classes (Carsel and Parrish 1988 [DIRS 147295], p. 755) based on a database of soil samples from 42 states (Carsel and Parrish 1988 [DIRS 147295], p. 758). The advantages of the Carsel and Parrish approach include its ease of use, it is a published approach, and its developers are highly respected.

A disadvantage to both approaches is that soils are collected from many types of climatic and depositional settings in the US and Europe and presumable mostly from agricultural areas in contrast to the desert environment at Yucca Mountain. Additionally, the collection methods and laboratory procedures, especially those related to the ROSETTA program database, are not documented for every sample. In Section 6.4, the results obtained with ROSETTA and by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) are compared to those from the analogous site database as part of method corroboration.

The analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) was selected for matching to Yucca Mountain soil samples because the soil and sediment samples in the database were collected from one general location, on or near Hanford in eastern Washington, which has an arid climate similar to that of the Yucca Mountain area. The average annual precipitation at Hanford is about 17.3 cm/yr (DOE 2001 [DIRS 177079], Section 3.2) compared to about 12.5 cm/yr for Yucca Mountain (BSC 2004 [DIRS 169734], Section 3.42). Hanford sediments have organic carbon content below 0.5 wt% (Truex et al. 2001 [DIRS 177078], Section 2.3.1.2). Organic carbon content in agricultural areas of Nye County range from about 0.006% to 0.70% (USDA 2006 [DIRS 176439]).

The analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) contains documented information on moisture retention, particle-size distribution, K_{sat} for 183 samples, sample collection methods, laboratory equipment, and laboratory procedures. Additionally, for samples that contain gravel, the moisture retention and K_{sat} data were corrected to account for the gravel content (Khaleel and Freeman 1995 [DIRS 175734], p. iii).

6.3.1 Parameters and Analogous Site Parameter Data Base

The analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) includes information on soil moisture retention, the parameters θ_r, θ_s, α, and n (van Genuchten et al. 1991 [DIRS 108810]), particle-size distribution, and K_{sat} for 183 samples (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B). Soil samples were collected primarily in conjunction with cable tool drilling activities. In most cases, splitspoon coring techniques were used to obtain samples. Laboratory analyses were performed at the Westinghouse Hanford Company Geotechnical Laboratory (GEL) or at the Pacific Northwest National Laboratory (PNNL) one of the DOE national laboratories. Particle-size distributions were determined on the less than 0.075 mm size fraction using a hydrometer. Dry sieving was used on the size fraction greater the 0.075 mm to less than 2 mm. At the GEL, moisture retention data were obtained using Tempe cells from saturation to –1,000 cm and the pressure plate extraction method for pressure heads from −1,000 to −15,000 cm. Constant head permeameter apparatus and methodology were used to determine K_{sat} (Khaleel and Freeman 1995 [DIRS 175734], Section 2.0).

Three test methods were used at the PNNL to determine moisture retention data: (1) the hanging water column method, (2) the pressure plate extraction method, and (3) the vapor equilibrium method. The K_{sat} was determined using a falling head permeameter (Khaleel and Freeman 1995 [DIRS 175734], Section 2.0). The procedures used at the GEL before 1993 produced the primary drainage curve, whereas procedures used at the PNNL produced the main drainage curve. In the properties report (Khaleel and Freeman 1995 [DIRS 175734], Sections 2.0 and 3.4 and Appendices A and B) an adjustment to the pre-1993 GEL generated data was applied to obtain the main drainage curve from the primary drainage curve (PDC).

Moisture retention and K_{sat} data in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) are laboratory-measured values that were first corrected, if necessary, for gravel content (Khaleel and Freeman 1995 [DIRS 175734], Sections 3.2, 3.3, and 5.1). Some data from the GEL, before 1993, also required adjustment to obtain the main drainage curve from the PDC as previously noted. Moisture retention data from the Tempe cell or hanging water column experiments for each individual sample were combined with the pressure-plate and vapor equilibrium data (Khaleel and Freeman 1995 [DIRS 175734], Section 5.1) to estimate the van Genuchten parameters θ_r, θ_s, and α and n (van Genuchten et al. 1991 [DIRS 108810]). The van Genuchten parameters were then fitted to the moisture retention data.

6.3.2 Matching Soil by Grain-Size Distribution

On the basis of soil texture, Yucca Mountain soil samples were matched to the analogous site sediment and soil samples. The Yucca Mountain soil sample texture information is provided as fraction sand, silt, and clay in three input DTNs: GS000383351030.001 [DIRS 148444], GS031208312211.001 [DIRS 171543], and MO0512SPASURFM.002 [DIRS 175955]. These input DTNs also contain sample location, sample depth, and fraction of rock fragment content.

The analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) contains percent sand, silt, and clay, which is the basis for matching samples. This database also contains percent rock and hydraulic parameters. In a few cases, exact texture matches have been identified. Generally, however, there is no exact match; for these cases, therefore, matches were selected based on those closely matching the percent of sand, silt, and clay and, secondarily, on those closely matching the sum of the silt and clay fractions.

The Euclidean distance (ED) is an indicator of how good the match is between any two samples, with the smaller ED values indicating better matches. An exact match has an ED of zero. The ED is applied to the sand, silt, and clay values by determining the difference between sand, silt, and clay fractions of any two soil samples. Because three parameters are considered, this application of ED represents the three-dimensional distance between the three parameters. The expression used to calculate ED between sand, silt, and clay for a pair of Yucca Mountain and analogous site samples is:

$$ED\ (3D) = [(Sand_{ymp} - Sand_{Hanford})^2 + (Silt_{ymp} - Silt_{Hanford})^2 + (Clay_{ymp} - Clay_{Hanford})^2]^{1/2}$$

This expression of ED is appropriate for all of the soil units except Soil Unit 6. Soil Unit 6 was sampled once and divided into five fractions, upon which sand sieve analysis tests were performed. The results are reported as fraction sand and fraction silt plus clay. The average two-dimensional ED calculated for Soil Unit 6 is 0.024. The limited data, however, precludes calculating the three-dimensional ED or associated statistics for Soil Unit 6. Appendix A contains a tabulation of ED values for each sample match. Table 6-6 provides a summary of the match quality, as expressed by the ED, in terms of mean ED, standard deviation, minimum value, maximum value, and count of the number of matches.

The following example describes how hydraulic properties for Soil Unit 1 are developed. Yucca Mountain soil sample MWV11-3, from output DTN: MO0605SEPDEVSH.002, was matched to analogous site soil sample D13-08, because both samples had the same fraction of sand, silt, and clay. As a test for goodness of match, the ED is calculated for the matched soil samples; smaller ED values indicate better matches. The resulting ED for this match is zero as shown in output DTN: MO0605SEPDEVSH.002, worksheet ‘MatchUncertainty’. Hydraulic parameter values, associated with the analogous database sample D13-08 (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B), are assigned to this Yucca Mountain sample and are tabulated in output DTN: MO0605SEPDEVSH.002, worksheet ‘HanfordMatchSoil1’. The tabulation includes the gravel content of the analogous site sample, which, in this case, contained no measurable gravel. Section 6.3.3 explains in detail the calculation method used for rock-fragment correction.

In the analogous site database, moisture values and K_{sat} were corrected for gravel content when gravel was found in the sample (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B). Analogous site soil sample D13-08 contains no gravel, therefore, removal of any gravel correction is unnecessary. Yucca Mountain sample MWV11-3 has a rock fragment content of 0.29 g/g (DTN: MO0512SPASURFM.002 [DIRS 175955], *YMPSoilProperties_PartI_ALL94andALL295.xls*, worksheet 'ALL295'). Moisture values and K_{sat} are corrected for rock fragment content as shown in output DTN: MO0605SEPDEVSH.002, worksheet 'RockFragCorrection'.

Table 6-6. Summary of Soil Sample Match Quality Based on Euclidean Distance

Soil Unit	Mean ED[a]	Standard Deviation	Minimum ED[a]	Maximum ED[a]	Count
1	0.0454	0.0362	0	0.1700	83
2	0.0357	0.0253	0	0.1338	105
3	0.0370	0.0257	0	0.1393	124
4	0.0219	0.0156	0	0.0566	24
5	0.0336	0.0193	0	0.1068	80
6	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]
7	0.0290	0.0130	0.0141	0.0510	14
9	0.0323	0.0143	0.01	0.0648	24

Source: Output DTN: MO0605SEPDEVSH.002, worksheet 'MatchUncertainty'.

[a] ED = Euclidean distance for matches between the analogous site samples and the Yucca Mountain soil samples based on fraction of sand, silt, and clay.

[b] NA = the value is not available because Soil Unit 6 was sampled once, the sample was divided into five fractions, and sand sieve analysis tests were performed on the five fractions. The results are reported as fraction sand and fraction silt plus clay. This precludes calculating the three-dimensional ED for Soil Unit 6.

6.3.3 Correction for Gravel (Rock Fragment) Content

The presence of rock fragments in the soil matrix affects infiltration and, therefore, the derivation of Yucca Mountain soil hydraulic properties must take into consideration the amount of rock fragments in the soil matrix. Methods for the correction of K_{sat} and moisture retention data for rock fragment content in soils are used frequently and are available from several sources. Two sources, as follows, provide methods used to correct derived values of K_{sat} and moisture contents for the presence of rock fragments in soil samples. The source of the correction to moisture content is the properties report (Khaleel and Freeman 1995 [DIRS 175734], Equation 5). The reliability of this source and the qualification of personnel and organizations generating the data are covered in Section 4.1.3. An additional source for this method was published in the peer-reviewed journal *Water Resources Research* (Khaleel and Relyea 1997 [DIRS 175733], Equation 2). The source of the correction to K_{sat} is from "Soil Containing Rock Fragments: Effects on Infiltration" (Brakensiek and Rawls 1994 [DIRS 175944], Equation 23), published in the peer-reviewed journal *Catena* of Elsevier Sciences.

Rock fragment correction methods for K_{sat} and moisture content have been published in peer-reviewed journals, generally having been passed through a commentary process and approved by subject matter experts before publication. Thus, the references discussed here are regarded as reliable sources and the methods outlined in this section were used in the same manner and context as the referenced sources.

The moisture content and K_{sat} data in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) were developed from laboratory tests that had the > 2mm size fraction screened out of the sample. The moisture content and K_{sat} data in the database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) were then corrected for gravel content. The moisture content and K_{sat} data (Khaleel and Freeman 1995 [DIRS 175734], Appendix A) must be adjusted back to values representative of zero rock content. They are then corrected for the specific Yucca Mountain soil rock fragment content.

Analogous site soil properties to be corrected include:

- Saturated hydraulic conductivity, K_{sat}
- Saturated moisture content, θ_s
- Field capacity, moisture content at –0.33 bar and –0.10 bar
- Wilting point, moisture content at –60 bar.

Corrections to K_{sat} were made in accordance with "Soil Containing Rock Fragments: Effects on Infiltration" (Brakensiek and Rawls 1994 [DIRS 175944], Equation 23). Corrections to moisture contents were made using the same procedure as that used in the properties report (Khaleel and Freeman 1995 [DIRS 175734], Equation 5).

The equation used to correct K_{sat} is (Brakensiek and Rawls 1994 [DIRS 175944], Equation 23):

$$\frac{K_b}{K_s} = 1 - m_g \qquad \text{(Eq. 6-1)}$$

where

K_b = Corrected saturated hydraulic conductivity

K_s = Saturated hydraulic conductivity of the fine fraction, 0% rock fragments

m_g = Weight fraction of the rock fragments.

The weight fraction of the rock fragments is from YMP data and given in units of g/g. Two other methods require the volume fraction of the rock fragments using the Peck and Watson equation (Brakensiek and Rawls 1994 [DIRS 175944], Equation 18), or the bulk void ratio and void ratio of the fine fraction using the Bouwer and Rice equation (Brakensiek and Rawls 1994 [DIRS 175944], Equation 19). An error analysis between the Bouwer and Rice equation and Equation 6-1 shows that the error between the two methods is not important for most practical applications (Brakensiek and Rawls 1994 [DIRS 175944], Figure 1). In this case, Equation 6-1 is applied using the weight fraction of the rock fragments, because of limitations of available data, allowing for the determination of bulk and fine void ratios.

The equation used to correct moisture contents (θ_r, θ_s, FC, and PWP) extracted from the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Equation 5) is:

$$\theta_b = \frac{w_f \dfrac{\rho_b}{\rho_w}}{1 + \dfrac{m_g}{m_f}} \qquad \text{(Eq. 6-2)}$$

where

θ_b = Corrected volumetric moisture content
w_f = Gravimetric moisture content
ρ_b = Bulk density of bulk soil; rock fragments and fines
ρ_w = Density of water
m_g = Weight fraction of the rock fragments
m_f = Weight fraction of fines.

Equation 6-2 was revised to directly use volumetric moisture content, θ, instead of the gravimetric moisture content, w_f, so that it could be used with available data. The revised equation is:

$$\theta_b = \frac{\theta_f}{1 + \dfrac{m_g}{m_f}} \qquad \text{(Eq. 6-3)}$$

where

θ_f = Uncorrected volumetric moisture content.

Although the majority of analogous site match samples have a rock fragment content of 0%, there are a few with rock fragment contents greater than 1%, a few as high as around 40%, but many ranging from 1% to 4%. A reverse rock fragment content correction was performed on the analogous site match samples to reset the hydraulic parameters to values representing samples with 0% rock fragment; 100% fines. After the reverse correction was performed on analogous site soil properties, the rock fragment correction was performed on the hydraulic parameters using the rock fragment contents from YMP data. Analogous site match samples with 0% rock fragment did not require this reverse rock fragment content correction.

Because the rock fragment content for Soil Unit 6 was not available in the textural analysis (DTN: GS000383351030.001 [DIRS 148444]), the rock fragment content was derived from a physical description (Section 6.2) of the material (DTN: GS940108315142.004 [DIRS 160344], p. 7). The rock fragment content is described as 5% to 50%. For the purpose of adding rock fragments to Soil Unit 6, the value of 27% rock fragments was chosen, which is the mid-point between 5% and 50% rounded down to the nearest whole number (Assumption 5.1).

6.3.4 Soil Unit Hydraulic Properties and Associated Statistics

Hydraulic parameters for each soil unit were developed (Section 6.3.2) by matching Yucca Mountain soil texture data with soil texture data provided in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) and then by correcting K_{sat} and moisture content parameters for rock fragment content. The parameters are as follows:

- Saturated hydraulic conductivity, K_{sat}
- FC at –0.33 bar and –0.10 bar matric potential
- PWP at –0.60 bar matric potential
- Saturated moisture content, θ_s
- WHC, which is defined as the difference between the FC and PWP (for alternate soil groups 1 and 2 only).

Additionally, correlations and uncertainties were developed for three soil groupings (Section 6.2.5). The base case soil group consists of Soil Units 1 to 5, as well as 6 (assumed to have same properties as Soil Unit 2), and 7 and 9, based on the description of mapped surficial deposits and their correlation to initial soil units defined for infiltration modeling (Table 6-4). For the base case soil grouping, descriptive statistics for the parameters, except for K_{sat}, are based on a normal distribution of the data. Descriptive statistics for K_{sat} are based on the natural log transformation of K_{sat}.

Multiple Yucca Mountain soil samples were collected, usually at a single location or coordinate, and it was initially important to be able to determine the lateral parameter variability, assuming a one-layer soil system. Therefore, single representative parameter values were calculated at each sample location for the base case soil grouping. For locations with multiple samples, the geometric mean of K_{sat} was determined (output DTN: MO0605SPASOILS.005) and the resultant value was then used to represent the locale K_{sat}. Spatial variability of K_{sat} was also described with the geometric mean and the standard error. The geometric mean of local K_{sat} values were determined and documented in output DTN: MO0605SPASOILS.005. For the base case soil grouping, descriptive statistics for K_{sat} are provided as the natural log transformation of the K_{sat} values and have been corrected for rock fragment content, as appropriate (output DTN: MO0605SEPDEVSH.002).

Commonly used averaging schemes, to determine effective K_{sat} values, include arithmetic, geometric, and harmonic means. The geometric mean results in an intermediate K_{sat} value between the harmonic and arithmetic mean and provides the best representation for the infiltration model area, given the potential for soil layering, small and large-scale heterogeneities, occurrence of sloping surfaces, and soil textures that are encountered in the infiltration model area (Domenico and Schwartz 1990 [DIRS 100569], p. 67). The harmonic mean has application in layered systems where flow is vertical and could be appropriate for a lumped-parameter mass-balance bucket-model, such as the infiltration model for Yucca Mountain (BSC 2006 [DIRS 177492]). The use of the harmonic mean would result in lower average K_{sat} values, which could underestimate infiltration, compared to those calculated using the geometric mean. The arithmetic mean is seldom used and would only be applicable in situations where the soils were uniform, non-layered, and homogeneous. Statistics were calculated using the standard Excel® DESCRIPTIVE STATISTICS function. Descriptive statistics for FC, PWP, and θ_s are based on a normal distribution and have been corrected for rock fragment content, as appropriate (output DTN: MO0605SEPDEVSH.002).

For the base case soil group, it was recognized that the data are too sparse to reliably determine correlations and spatial variability for many of the soil units. Therefore, two alternative soil groupings are considered (Section 6.2.5). For both alternatives, K_{sat} is assumed to be lognormally distributed (Section 6.3.4.1). The parameters FC, PWP, and θ_s are initially assumed to be normally distributed to allow for comparison to the base case soil group, but are further evaluated and in some cases other distributions types are recommended (Sections 6.3.4.2 and 6.3.4.3; Appendix D). An additional parameter WHC is calculated for the two alternative groupings only. The WHC is the difference between the FC moisture content and the PWP moisture content, and is provided for the two alternative soil groupings to accommodate alterative infiltration model inputs (Sections 6.3.4.2 and 6.3.4.3).

6.3.4.1 Base Case Soil Grouping Hydraulic Properties and Statistics

The base case group consists of Soil Units 1 to 5, as well as 6 (assumed to have the same properties as Soil Unit 2), and 7 and 9. The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated for each hydraulic parameter (Table 6-7).

Saturated hydraulic conductivity is found to be lognormally distributed, based on the following information. Because of this, descriptive statistics for K_{sat} (Table 6-7) are based on the natural log transformation of K_{sat} where the variation is quantified by the standard deviation of the natural logarithm transformed data, consistent with the recommendation by Gelhar (1993 [DIRS 101388], p. 2). This finding is an appropriate scientific analysis assumption because K_{sat} has been observed to vary over four orders of magnitude in apparently homogeneous material (Gelhar 1993 [DIRS 101388], p. 1) and is often found to have a lognormal distribution (Meyer et al. 1997 [DIRS 176004], Appendix A; Khaleel and Freeman 1995 [DIRS 175734], Table 3; Istok et al. 1994 [DIRS 176890], p. 1046). In addition, there is a large body of direct evidence to support the statement that the probability density function for hydraulic conductivity is lognormal (Freeze and Cherry 1979 [DIRS 101173], Section 2.4).

The K_{sat} distributions of four of the six texture-based soils categories, in the analogous site database, were found to be lognormal and the remaining two soils categories were fit to a log ratio distribution (Khaleel and Freeman 1995 [DIRS 175734], Table 3). The K_{sat} distributions of 12 soil types, based on USDA soil texture classification, were evaluated in NUREG/CR-6565 for approximately 5,700 soil samples (Meyer et al. 1997 [DIRS 176004], Table 2-1 and Appendix A). NUREG/CR-6565 reports that saturated hydraulic conductivity for 10 of the 12 soil textures have a lognormal distribution (Meyer et al. 1997 [DIRS 176004], Appendix A). NUREG/CR-6565 also reports that saturated hydraulic conductivity for two of the 12 soil textures have a beta distribution (Meyer et al. 1997 [DIRS 176004], Appendix A). These references support the scientific analysis assumption that K_{sat} is lognormally distributed.

Table 6-7. Summary of Soil Hydraulic Parameter Values and Statistics for the Base Case Soils Group

Statistical Parameter	Ln Transformed Saturated Hydraulic conductivity (Ln cm/sec) (a)	Field Capacity, Volumetric Moisture Content (dimensionless) at –0.33 bar (a)	Field Capacity, Volumetric Moisture Content (dimensionless) at –0.10 bar (b)	Permanent Wilting Point, Volumetric Moisture Content (dimensionless) at –60 bar (a)	θ_s Volumetric Moisture Content (dimensionless) (a)	Rock Fragment Content Percent (c)
Soil Unit 1						
Mean	–9.3727	0.14	0.21	0.05	0.25	48
Standard Error	0.3092	0.02	0.02	0.01	0.02	
Median	–9.2989	0.13	0.18	0.05	0.27	
Standard Deviation	1.0711	0.07	0.08	0.02	0.08	
Minimum	–11.9450	0.07	0.11	0.02	0.14	
Maximum	–7.9449	0.30	0.34	0.07	0.35	
Count	12	12	12	12	12	
Soil Unit 2						
Mean	–9.2704	0.13	0.19	0.04	0.22	50
Standard Error	0.1998	0.02	0.02	0.004	0.02	
Median	–9.3620	0.12	0.17	0.04	0.19	
Standard Deviation	0.7736	0.07	0.08	0.01	0.08	
Minimum	–11.0786	0.05	0.08	0.02	0.12	
Maximum	–8.0413	0.37	0.42	0.08	0.43	
Count	15	15	15	15	15	
Soil Unit 3						
Mean	–9.4760	0.09	0.14	0.03	0.17	58
Standard Error	0.2109	0.01	0.01	0.003	0.01	
Median	–9.8112	0.08	0.14	0.02	0.16	
Standard Deviation	1.1161	0.04	0.05	0.02	0.06	
Minimum	–10.9812	0.03	0.06	0.01	0.07	
Maximum	–6.3679	0.18	0.26	0.07	0.31	
Count	28	28	28	28	28	

Table 6-7. Summary of Soil Hydraulic Parameter Values and Statistics for the Base Case Soils Group (Continued)

Statistical Parameter	Ln Transformed Saturated Hydraulic conductivity (Ln cm/sec) (a)	Field Capacity, Volumetric Moisture Content (dimensionless) at –0.33 bar (a)	Field Capacity, Volumetric Moisture Content (dimensionless) at –0.10 bar (b)	Permanent Wilting Point, Volumetric Moisture Content (dimensionless) at –60 bar (a)	θ_s Volumetric Moisture Content (dimensionless) (a)	Rock Fragment Content Percent (c)
Soil Unit 4						
Mean	–9.7961	0.04	0.06	0.01	0.13	63
Standard Error	0.4948	0.01	0.01	0.00	0.02	
Median	–9.9554	0.03	0.06	0.01	0.12	
Standard Deviation	1.2119	0.02	0.03	0.01	0.05	
Minimum	–11.1974	0.01	0.02	0.003	0.07	
Maximum	–7.9170	0.07	0.11	0.03	0.20	
Count	6	6	6	6	6	
Soil Unit 5						
Mean	–9.4166	0.15	0.23	0.04	0.26	38
Standard Error	0.1210	0.01	0.01	0.003	0.01	
Median	–9.3944	0.14	0.22	0.04	0.24	
Standard Deviation	0.4688	0.04	0.05	0.01	0.05	
Minimum	–10.1132	0.09	0.17	0.03	0.19	
Maximum	–8.4618	0.24	0.35	0.07	0.37	
Count	15	16	16	16	16	
Soil Unit 6						
Mean	–9.2704	0.13	0.19	0.04	0.22	50
Standard Error	0.1998	0.02	0.02	0.004	0.02	
Median	–9.3620	0.12	0.17	0.04	0.19	
Standard Deviation	0.7736	0.07	0.08	0.01	0.08	
Minimum	–11.0786	0.05	0.08	0.02	0.12	
Maximum	–8.0413	0.37	0.42	0.08	0.43	
Count	n/a	n/a	n/a	n/a	n/a	

Table 6-7. Summary of Soil Hydraulic Parameter Values and Statistics for the Base Case Soils Group (Continued)

Statistical Parameter	Ln Transformed Saturated Hydraulic conductivity (Ln cm/sec) (a)	Field Capacity, Volumetric Moisture Content (dimensionless) at –0.33 bar (a)	Field Capacity, Volumetric Moisture Content (dimensionless) at –0.10 bar (b)	Permanent Wilting Point, Volumetric Moisture Content (dimensionless) at –60 bar (a)	θ_s Volumetric Moisture Content (dimensionless) (a)	Rock Fragment Content Percent (c)
Soil Unit 7						
Mean	–9.3676	0.15	0.23	0.05	0.25	44
Standard Error	0.1510	0.01	0.01	0.003	0.02	
Median	–9.4711	0.14	0.21	0.04	0.23	
Standard Deviation	0.3700	0.03	0.04	0.01	0.04	
Minimum	–9.8045	0.13	0.19	0.04	0.21	
Maximum	–8.7679	0.19	0.28	0.06	0.30	
Count	6	6	6	6	6	
Soil Unit 9						
Mean	–10.1075	0.09	0.17	0.03	0.20	57
Standard Error	0.1491	0.02	0.01	0.005	0.02	
Median	–10.1846	0.08	0.16	0.02	0.20	
Standard Deviation	0.2981	0.03	0.03	0.01	0.03	
Minimum	–10.3780	0.07	0.14	0.02	0.16	
Maximum	–9.6827	0.14	0.21	0.04	0.23	
Count	4	4	4	4	4	

NOTES: Soil Unit 6 is assumed to have the same hydraulic properties as Soil Unit 2 and the sample “count” is set to n/a.

Letters in parentheses refer to the following sources:

(a) Output DTN: MO0605SPASOILS.005, *Rev5SummarySoilHydraulicParameters_5-1-06.xls*
(b) Output DTN: MO0605SEPFCSIM.000, *SoilUnitX_Summary_1-10barFC_5-25-06.xls* where X is the soil unit number.
(c) Output DTN: MO0605SEPDEVSH.002, *SoilUnitX_HydProps_5-1-06.xls*, worksheet ‘YMPSoilUnitX’ where X is the soil unit number.

For the base case soil units, the statistics provided for FC, PWP, and θ_s (Table 6-7) are for comparison purposes and are based on the scientific analysis assumption that these parameters are all normally distributed. The available sample size (count) of FC, PWP, and θ_s (Table 6-7), however, developed with the pedotransfer matching approach, are not sufficient to reliably determine distribution types for most of the soil units. In addition, the mixture of multiple soil textures within a soil unit, in some cases, may result in bimodal distributions that further complicate the ability to determine the parameter distribution type.

The description of soils in DTN: GS960408312212.005 [DIRS 146299] allow for grouping of surficial deposits of similar characteristics, specifically the amount of clay accumulation in the deposits, the extent of pedogenic calcium carbonate accumulated in the deposits, and the variation in the particle size distribution (Section 6.2). Nonetheless, with this system, there is resulting textural overlap between soil units (Section 6.2) when compared to soil classifications based on the USDA soil triangle (USDA 1999 [DIRS 152585], Exhibit 618-8).

Grain-size analysis of Yucca Mountain soils indicates that about 68% of the soils are classified sandy loam, followed by loamy sand at 27%, and sand at 5% (DTNs: GS031208312211.001 [DIRS 171543] and MO0512SPASURFM.002 [DIRS 175955]), based on the USDA soil triangle (USDA 1999 [DIRS 152585], Exhibit 618-8).

For comparison, Table 6-8 provides the recommended soil hydraulic-parameter distributions types for the predominant Yucca Mountain soil textures, sandy loam, loamy sand, and sand, based on NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], Tables A-1 to A-3). These recommended distributions (Table 6-8) are for discrete soil texture groups and are not the same as the base case soil units, which contain multiple soil textures. Thus, the recommendations are not directly applicable to the Yucca Mountain soil units. The mixture of soil textures within the Yucca Mountain soil units may also be responsible for bimodal parameter distributions observed for some parameters (Appendix D). Still, there could be justification to assume that FC and PWP are normally and lognormally distributed, based on the recommendations in Table 6-8. These recommendations, however, are based on evaluations of separate textures, not mixtures of textures such as those encountered with the soil in the infiltration model area.

Normal or lognormal distributions for these parameters could result in combinations of FC and PWP that are beyond physically realistic values when considering sampling plus or minus two standard deviation (or standard errors) from the mean value. Therefore, if the parameters FC, PWP, and θ_s developed for the base case soils group are used as stochastic inputs to a replacement infiltration model, then a piece-wise uniform distribution should be used to minimize the occurrence of physically unrealistic parameter combinations and to capture uncertainty.

Table 6-8. Soil Hydraulic Parameter Statistical Distribution Comparison

Parameter	Recommended Yucca Mountain Distribution for Base Case Soil Grouping (This Analysis)	Recommended NRC Distribution for Sandy Loam	Recommended NRC Distribution for Loamy Sand	Recommended NRC Distribution for Sand
θ_s	Piecewise uniform	Normal	Normal	Normal
Field Capacity	Piecewise uniform	Lognormal	Lognormal	Lognormal
Permanent Wilting Point	Piecewise uniform	Normal	Normal	Lognormal
K_{sat}	Lognormal	Lognormal	Beta	Beta

Sources: NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], Tables A-1 to A-3); output DTN: MO0605SPASOILS.005.

NOTE: NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], Section 2.2) took field capacity to be the moisture content at which unsaturated hydraulic conductivity is equal to 1E-08 cm/sec and the permanent wilting point at a matrix potential of –15 bar.

NRC = U.S. Nuclear Regulatory Commission.

Piece-wise uniform distributions for each of these parameters were developed in output DTN: MO0605SPASOILS.005. To ensure that the data range captures the uncertainty, the data were then compared to expected ranges of values based on soil texture (output DTN: MO0605SEPDEVSH.002, *SoilUnitX_HydProps_5-1-06.xls*, worksheet 'Expected Values', where X represents a soil unit number) and minimum and or maximum values were added to the distribution when they were not included in the data range (output DTN: MO0605SPASOILS.005, *Rev5SoilUnitX_Piecewise_uniform_V1.5_04_14_2006.xls*, worksheet 'input and sorting'). Potential correlations between K_{sat}, FC, PWP, and θ_s are evaluated by considering both the calculated correlation matrix for the data (output DTN: MO0605SPASOILS.005) and values in the literature for similar texture soils. The Excel® function CORREL is used to calculate correlation. Because it is possible that some correlations cannot be estimated, for instance when two variables do not have any value in a common location, the initial correlation matrix is recalculated using the Excel® function ISERROR, which suppresses any eventual error such as #DIV/0!. The calculated correlations (output DTN: MO0605SPASOILS.005) are provided in Table 6-9.

Table 6-9. Estimate of Correlation between Soil Hydraulic Parameters for Base Case Soil Grouping

	Soil Unit 1			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	0.09	0.14	0.24
Field Capacity		1	0.81	0.84
Permanent Wilting Point			1	0.86
θ_s				1
	Soil Unit 2 and Soil Unit 6			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	0.31	0.11	0.27
Field Capacity		1	0.81	0.93
Permanent Wilting Point			1	0.80
θ_s				1

Table 6-9. Estimate of Correlation between Soil Hydraulic Parameters for Base Case Soil Grouping (Continued)

	Soil Unit 3			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	0.45	0.66	0.70
Field Capacity		1	0.87	0.79
Permanent Wilting Point			1	0.78
θ_s				1
	Soil Unit 4			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	0.02	0.47	0.78
Field Capacity		1	0.21	0.18
Permanent Wilting Point			1	0.69
θ_s				1
	Soil Unit 5			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	0.47	0.52	0.28
Field Capacity		1	0.88	0.87
Permanent Wilting Point			1	0.88
θ_s				1
	Soil Unit 7			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	–0.08	0.29	0.05
Field Capacity		1	0.87	0.98
Permanent Wilting Point			1	0.95
θ_s				1
	Soil Unit 9			
	Ln K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
Ln K_{sat}	1	0.99	1.00	0.72
Field Capacity		1	0.99	0.77
Permanent Wilting Point			1	0.69
θ_s				1

Source: Output DTN: MO0605SPASOILS.005, *Rev5SoilUnitX_Piecewise_uniform_V1.5_04_14_2006.xls*, worksheet 'input and sorting' where X is the soil unit number.

NOTES: Estimated correlations for Soil Unit 9 are unrealistically large because there are only four values. Field capacity is the moisture content at a matric potential of –0.33 bar. Permanent wilting point in the moisture content at a matric potential of –60 bar. θ_s is the saturated moisture content. Correlations for K_{sat} are for the natural log transformed K_{sat} data. No entry is intended for shaded cells.

For the base case soil grouping, there are two limitations to the calculated correlation using hydraulic parameter values derived from Yucca Mountain soil texture data. The number of spatially distributed values are too sparse for some soil units (Table 6-7) and the matching approach may result in more correlation than would exist if site-specific Yucca Mountain hydraulic data were available, because some Yucca Mountain soil textures are very similar and best fit the same sample in the analogous database. Therefore, potential correlations between K_{sat} and the other parameters from the literature are also considered.

NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], Appendix B) provides estimated correlations between K_{sat} and the other parameters based on a soils database initially developed by Carsel and Parish (1988 [DIRS 147295]). The soils are grouped into 12 USDA texture classes. NUREG/CR-6565 correlations between K_{sat} and FC, PWP, and θ_s, are tabulated in Table 6-10 (Meyer et al. 1997 [DIRS 176004], Appendix B) for the USDA soil textures typically found in the infiltration model area (Figure 6-1). These differences between the estimated correlations (Table 6-9) and literature values (Table 6-10) are due in part to the differences in how the soils are grouped and may also result from a combination of limited sample size, the use of different soil databases, regression equations, and analytical procedures in fitting parameter values to water retention data, as discussed in NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], Section 5).

Soil Unit 6 is assumed to have the same hydraulic properties as developed for Soil Unit 2, including parameter correlations (Section 6.2.5). This is a scientific analysis assumption. The effect associated with this assumption is small because Soil Unit 6 comprises less than 5% of the soils in the infiltration model area (Table 6-3). The closest occurrence of Soil Unit 6 is approximately 1.5 mi east of the lower extent of the projected repository footprint (Figure 6-1) and there are no occurrences of Soil Unit 6 over the projected repository footprint.

For Soil Unit 9, the calculated correlations between K_{sat} and FC, PWP, and θ_s, (Table 6-9) are unrealistically large because there are only four spatially distributed values for this soil unit. Soil Unit 9 is composed of approximately 85% sandy loam and 15% loamy sand, and most closely resembles Soil Unit 5 based on soil texture (Section 6.2). Soil Unit 5 also has 15 laterally distributed values of K_{sat} and 16 values of FC, PWP, and θ_s, from which estimates of parameter correlation were calculated (output DTN: MO0605SPASOILS.005). Therefore, the correlations for Soil Unit 9 are assumed to be the same as calculated for Soil Unit 5.

The limitations of Yucca Mountain data, and literature findings on correlations, are motivation to develop an alternative data input scheme for the replacement infiltration model that would be independent of distribution type and correlations, and still be able to capture uncertainty. The development of data for such a scheme is discussed in Sections 6.3.4.2 and 6.3.4.3.

Table 6-10. Estimate of Correlation between Parameters for Soil Textures Typically Found in the Infiltration Model Area

	Sand			
	K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
K_{sat}	1	–0.67	–0.50	0.00
Field Capacity		1	0.94	0.15
Permanent Wilting Point			1	−0.01
θ_s				1
	Loamy Sand			
	K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
K_{sat}	1	–0.58	–0.35	0.01
Field Capacity		1	0.85	0.27
Permanent Wilting Point			1	0.00
θ_s				1
	Sandy Loam			
	K_{sat}	**Field Capacity**	**Permanent Wilting Point**	**θ_s**
K_{sat}	1	–0.51	–0.25	0.01
Field Capacity		1	0.78	0.38
Permanent Wilting Point			1	0.03
θ_s				1

Source: NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], Tables B-1 to B-3).

NOTES: Field capacity is defined as the moisture content at which unsaturated hydraulic conductivity is equal to 1E-08 cm/sec. Permanent wilting point in the moisture content at a matric potential of –15 bar. θ_s is the saturated moisture content. No entry is intended for shaded cells.

6.3.4.2 Alternate Soil Group 1 Hydraulic Properties and Statistics

Alternate soil group 1 consists of four soil units (Section 6.2.5), which are combinations of the eight base case soil units. The four soil units of alternate soil group 1 are: Soil Unit 1, Soil Unit 2-6, Soil Unit 3-4, and Soil Unit 5-7-9. The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated for each hydraulic parameter (Table 6-11) for each of the four soil units. Saturated hydraulic conductivity is found to have a log distribution for each of these soil units based on the same rationale as provided for the base case grouping (Section 6.3.4.1). The statistics provided for K_{sat} (Table 6-11) are based on the natural log transformation of K_{sat} where the variation is quantified by the standard deviation of the natural logarithm transformed data, consistent with Gelhar (1993 [DIRS 101388], p. 2).

Table 6-11. Summary of Soil Hydraulic Parameter and Statistics for Alternate Soil Group 1

Statistical Parameter	Ln Transformed Saturated Hydraulic Conductivity (Ln cm/sec)	FC, Volumetric Moisture Content (dimensionless) at –0.33 bar	FC, Volumetric Moisture Content (dimensionless) at –0.10 bar	PWP, Volumetric Moisture Content (dimensionless) at –60 bar	WHC, Volumetric Moisture Content (dimensionless) for FC at –0.33 bar	WHC, Volumetric Moisture Content (dimensionless) for FC a –0.10 bar	θ_s Volumetric Moisture Content (dimensionless)
Soil Unit 1							
Mean	–9.436	0.125	0.183	0.040	0.085	0.125	0.230
Standard Error	0.1963	0.011	0.012	0.003	0.009	0.011	0.013
Median	–9.371	0.100	0.160	0.032	0.067	0.100	0.254
Standard Deviation	1.607	0.096	0.111	0.025	0.079	0.096	0.118
Minimum	–13.363	0.018	0.026	0.007	0.004	0.018	0.040
Maximum	–4.818	0.465	0.488	0.091	0.382	0.465	0.490
Count	67	81	81	81	81	81	81
Soil Unit 2-6							
Mean	–9.105	0.123	0.177	0.037	0.086	0.140	0.208
Standard Error	0.1753	0.010	0.012	0.003	0.008	0.0097	0.012
Median	–9.348	0.082	0.141	0.031	0.057	0.110	0.182
Standard Deviation	1.498	0.102	0.118	0.026	0.084	0.099	0.121
Minimum	–13.212	0.005	0.011	0.002	0.000	0.002	0.017
Maximum	–4.853	0.460	0.482	0.130	0.378	0.400	0.485
Count	73	104	104	104	104	104	104
Soil Unit 3-4							
Mean	–9.571	0.075	0.123	0.024	0.051	0.098	0.157
Standard Error	0.1371	0.004	0.006	0.001	0.003	0.005	0.007
Median	–10.008	0.066	0.106	0.020	0.043	0.081	0.141
Standard Deviation	1.476	0.048	0.072	0.017	0.038	0.062	0.078
Minimum	–12.270	0.008	0.011	0.002	0.000	0.003	0.027

Table 6-11. Summary of Soil Hydraulic Parameter and Statistics for the Alternative Soil Group 1 (Continued)

Statistical Parameter	Ln Transformed Saturated Hydraulic Conductivity (Ln cm/sec)	FC, Volumetric Moisture Content (dimensionless) at –0.33 bar	FC, Volumetric Moisture Content (dimensionless) at –0.10 bar	PWP, Volumetric Moisture Content (dimensionless) at –60 bar	WHC, Volumetric Moisture Content (dimensionless) for FC at –0.33 bar	WHC, Volumetric Moisture Content (dimensionless) for FC a –0.10 bar	θ_s Volumetric Moisture Content (dimensionless)
Soil Unit 3-4 (Continued)							
Maximum	–4.865	0.216	0.332	0.082	0.151	0.275	0.368
Count	116	137	137	137	137	137	137
Soil Unit 5-7-9							
Mean	–9.593	0.134	0.208	0.039	0.095	0.169	0.233
Standard Error	0.0792	0.006	0.007	0.002	0.004	0.006	0.008
Median	–9.498	0.136	0.210	0.036	0.094	0.172	0.232
Standard Deviation	0.662	0.048	0.062	0.016	0.035	0.048	0.067
Minimum	–11.913	0.015	0.032	0.004	0.011	0.028	0.039
Maximum	–8.407	0.237	0.348	0.072	0.174	0.284	0.366
Count	70	78	78	78	78	78	78

Source: Output DTN: MO0605SEPALTRN.000 where data for Soil Units 1, 2-6, 3-4, and 5-7-9 are found in *SoilUnit1FC1-10and1-3Bar_5-30-06.xls*, worksheet 'HydraulicPropandStatistics,' *SoilUnit2-6FC1-10and1-3Bar_5-30-06.xls*, worksheet 'HydraulicPropandStatistics,' *SoilUnit3-4FC1-10and1-3Bar_5-30-06.xls*, worksheet 'HydraulicPropandStatistics,' and *SoilUnit5-7-9 FC1-10and1-3Bar_5-30-06.xls*, worksheet 'HydraulicPropandStatistics,' respectively.

FC = field capacity; PWP = permanent wilting point; WHP = water holding capacity.

The four soil units in alternate soil group 1 and the statistics provided for FC, PWP, and θ_s (Table 6-11) are for comparison purposes and are based on the assumption that these parameters are all normally distributed. Two approaches are considered for developing stochastic model inputs for FC, PWP, and θ_s. The first approach is to attempt to determine the parameter distribution types and statistics for each of the three parameters (Appendix D). Tentative normal and lognormal distribution fits were attempted for each of the four soil units. The normal distribution did not fit any of the data. The parameters FC at –0.10 bar, WHC at –0.10 bar, PWP, and θ_s fit a lognormal distribution for Soil Unit 1. All of the parameters fit the lognormal distribution for Soil Unit 2-6. The parameters FC at –0.10 bar and WHC at –0.10 bar fit a lognormal distribution for Soil Unit 3-4. The WHC at –0.33 bar fit a lognormal distribution for Soil Unit 5-7-9.

Parameters that did not fit normal or lognormal were fit to a beta distribution (Appendix D). Infiltration model inputs would be sampled from a range of FC and PWP values based on these distributions and associated statistics that for some cases would result in physically impossible combinations. For instance, combinations of FC and PWP could be sampled from the distributions that would result in WHC values near zero. This may be overcome by limiting the sample ranges, but such limitation may result in underestimating uncertainty.

Thus a second approach, which is the recommended approach, is considered. This approach would preserve the estimate of uncertainty and still provide physically meaningful parameter values. This second approach is based on using PWP and WHC as replacement infiltration model inputs, from which FC is calculated in during model execution. The range of WHC samples would incorporate both definitions of FC. The minimum WHC value would be the FC at –0.33 bar minus the PWP minus the standard error; the upper WHC values would be the FC at –0.10 minus the PWP plus the standard error. This captures the uncertainty in the definition of FC as well as the uncertainty in the data, as expressed by the standard error. If θ_s is considered a stochastic parameter in a replacement infiltration model, then the values of θ_s would be sampled from the distribution and statistics shown in Appendix D.

6.3.4.3 Alternate Soil Group 2 Hydraulic Properties and Statistics

Alternate soil group 2 consists of grouping the eight base case soil units into one soil unit (Section 6.2.5). The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated for each of the hydraulic parameters (Table 6-12) for this soil unit. As with the base case and with alternate soil group 1, K_{sat} is assumed to have a log distribution for each soil unit, based on the rationale provided in Section 6.3.4.1. The statistics provided for K_{sat} (Table 6-12) are based on the natural log transformation of K_{sat} where the variation is quantified by the standard deviation of the natural logarithm transformed data, consistent with Gelhar (1993 [DIRS 101388], p. 2).

Table 6-12. Summary of Soil Hydraulic Parameters and Statistics for Alternate Soil Group 2 – All Soils Combined into One Group

Statistical Parameter	Ln Transformed Saturated Hydraulic Conductivity (Ln cm/sec)	FC, Volumetric Moisture Content (dimensionless) at –0.33 bar	FC, Volumetric Moisture Content (dimensionless) at –0.10 bar	PWP, Volumetric Moisture Content (dimensionless) at –60 bar	WHC, Volumetric Moisture Content (dimensionless) for FC at –0.33 bar	WHC, Volumetric Moisture Content (dimensionless) for FC at –0.10 bar	θ_s Volumetric Moisture Content (dimensionless)
Mean	–9.444	0.109	0.166	0.034	0.076	0.132	0.200
Standard Error	0.0768	0.004	0.005	0.001	0.003	0.004	0.005
Median	–9.517	0.091	0.155	0.028	0.060	0.119	0.185
Standard Deviation	1.386	0.080	0.098	0.022	0.064	0.082	0.103
Minimum	–13.363	0.005	0.011	0.002	0.000	0.002	0.017
Maximum	–4.818	0.465	0.488	0.130	0.382	0.405	0.490
Count	326	400	400	400	400	400	400

Source: Output DTN: MO0605SEPALTRN.000, *AllSoilsFC1-10and1-3Bar_5-30-06.xls.*

FC = field capacity; PWP = permanent wilting point; WHP = water holding capacity.

For the one soil unit in alternate soil group 2, the statistics provided for FC, PWP, and θ_s (Table 6-12) are for comparison purposes and are based on the tentative assumption that these parameters are all normally distributed. As with alternate soil group 1 (Section 6.3.4.2), two approaches are considered for developing stochastic model inputs for FC, PWP, and θ_s. The first approach is to determine the parameter distribution types and statistics for each of the three parameters (Appendix D). Tentative normal and lognormal distribution fits were attempted for each of the four soil units. The normal distribution did not fit any of the data (Appendix D). All the parameters, however, fit a lognormal distribution for this alternative soil grouping.

6.4 UNCERTAINTIES AND POTENTIAL EFFECTS ON ANALYSIS

The qualitative discussion in this section addresses the uncertainties and potential effects on the analysis. Uncertainties are identified with respect to the following:

- Effect of pedogenic products on soil hydraulic parameter values
- Yucca Mountain soil sampling methods, including spatial locations of the samples used to make the matches
- Local Nevada Test Site and Nye County data
- Corroboration of YMP soils and analogous site soil and sediment hydraulic parameter
- Process used in matching the YMP soil textural data to the soil data in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B).

The hydraulic parameter data generated in this analysis are intended for use only in a replacement infiltration model (Section 1).

6.4.1 Effect of Pedogenic Products on Soil Hydraulic Parameter Values

A potential source of uncertainty in the hydraulic properties of the soils of Yucca Mountain is the influence of pedogenic products on infiltration processes. Soils developed on unconsolidated surficial deposits show an increasing degree of desert pavement development, argillic accumulation, and pedogenic carbonate cementation with aging of the deposit. Because the formation of each of these is directly related to the passage of time, the younger soil deposits are least affected.

Formation of desert pavements involves the eventual creation of an almost continuous "pavement" of very low permeability rock clasts at the ground surface, underlain by an accumulation of silt- and clay-size material of eolian origin. Development of a pedogenic vesicular "A" horizon (an Av horizon) underneath the pavement has been shown to lead to higher WHC; 90% of the variation in log K_{sat} could be attributed to the soil age (Young et al. 2004 [DIRS 176416], Figure 5).

It was concluded that lower hydraulic conductivities of older soils limit infiltration, resulting in either an increase in runoff, or a retention of water in the most bioavailable portion of the soil profile, perhaps allowing the soil-plant system to be less susceptible to drought (Young et al. 2004 [DIRS 176416]). The presence of desert pavement, which is present in varying degrees of maturity on the Yucca Mountain soil units (Table 6-4), is interpreted as contributing to lower hydraulic conductivity values than those obtained by considering only particle size distributions.

The pedogenic process that results in the formation of an argillic horizon is due to the accumulation of clay through time in an illuviated horizon. The sample identifiers of some samples refer to these illuviated horizons by the designation of a "B" soil horizon; for example, MWVP15-3Btkqb in Soil Unit 2 (output DTN: MO0605SEPDEVSH.002). The downward movement of clays in a soil horizon is attributed to water percolation and capillarity. The presence of carbonate may play an effective role in stopping the downward moving clay. Soil Unit 1, for example, is defined as a unit having an argillic horizon above a petrocalcic horizon that is within 100 cm of the ground surface. The result is a near-surface soil horizon that has increased clay content relative to the parent material. In samples having increased clay content, the hydraulic conductivity is decreased (Freeze and Cherry 1979 [DIRS 101173], Table 2.2 and Section 8.7). Because the development of hydraulic properties (Section 6.3) is based on particle size distribution in soils, the accumulation of pedogenic clays in an argillic horizon are captured in a particle-size analysis as a sample having an increase in clay-size particles, compared to its parent material.

The accumulation of pedogenic carbonate in desert soils eventually, through time, leads to the formation of petrocalcic or cemented soil. The soils at Yucca Mountain are in part differentiated by the amount and depth of occurrence of the petrocalcic horizon (Section 6.2.2). When water infiltrates into soil, it commonly carries downwind any dissolved calcium carbonate or other salts, derived from either weathered limestone or playa deposits. The precipitation of pedogenic calcium carbonate in soils occurs at the average depth of wetting, where the evaporation of water leads to the precipitation of fine carbonate crystals, approximately 10 µm in diameter (Duniway et al. 2004 [DIRS 176417]).

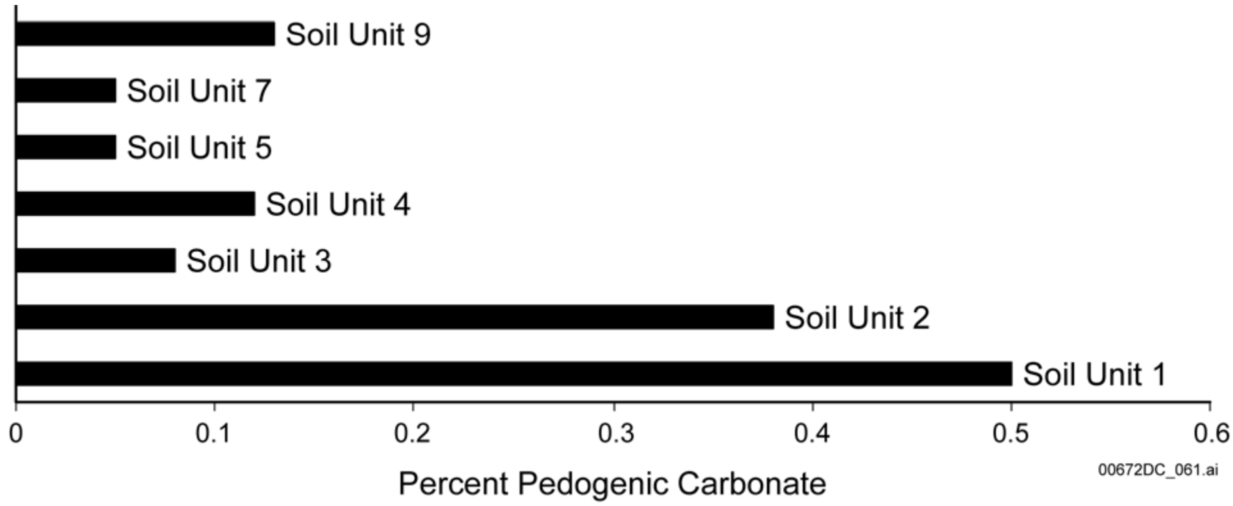
Initially, carbonate forms along roots on the undersides of gravel clasts and on soil particle surfaces (Stage I carbonate soil). With time, carbonate accumulates as disseminated masses in soil pores (Stage II), eventually completely plugging the soil pores (Stage III) and restricting downward water movement, which produces a laminar carbonate layer (Stage IV). This accumulation can change a coarse textured soil from a matrix of large pores to a matrix dominated by fine pores. The amount of carbonate present in gravelly soils, which is a characteristic of the Yucca Mountain soils, was estimated by Machette (1985 [DIRS 104660], Table 1) in various stages of carbonate soil development: Stage I – 0% to 2%, Stage II – 3% to 10%, Stage III – 11% to 25%, and Stage IV – 26% to 50%.

Due to the small grain size of disseminated carbonate in Stage I to Stage III carbonate soils, the increase in carbonate may be captured, in part, in the soil texture analysis as an increase in clay-sized particles. The accumulation of the carbonate reduces the pore size in the gravelly deposits and, thus, would effectively reduce the saturated conductivity of the material, which is similar to the effect from increasing the proportion of silt or clay in the soil. This effect is corroborated by a study in New Mexico, where plugged soil horizons (Stage III pedogenic carbonate) were measured as having 18% to 24% available WHC, compared with 5% to 15% for loamy sand and clay loam (no carbonate accumulation), respectively, and 5% to 12% for Stage IV laminar carbonate horizon (Duniway et al. 2004 [DIRS 176417]). Because of the similarity in grain size, the effect of pedogenic Stage I to Stage III on the hydraulic parameters for infiltration modeling is captured to some extent in the particle size analysis.

The effect of cemented petrocalcic material in the soil profile is less likely to be captured in the approach used in Section 6.3, because the particle size analysis is performed on the <2mm size fraction (NWM-USGS-HP-263, R0; YMP-USGS-HP-263, R0-M1) and pieces of cemented pedogenic carbonate or carbonate cemented to the bottom of gravel clasts would be retained on the >2mm sieves, along with gravel clasts. Hydraulic conductivity is moderately low to very low through a petrocalcic horizon (USDA 1999 [DIRS 175948], p. 48). Measurements of saturated hydraulic conductivity on laminated carbonate in fracture fill (DTN: GS950708312211.003 [DIRS 146873], Table S98356_004), considered analogous to laminar calcic soil horizons, have a geometric mean of 1.087E-06 cm/sec (Assumption 5.2). This value is approximately two orders of magnitude lower than the values derived for the soil units in Section 6.3. It is anticipated that saturated hydraulic conductivity values for soils exhibiting the less developed Stage I and Stage II carbonate soils would fall between the value of 1.087E-06 cm/sec (Assumption 5.2) allocated to the Stage IV soils, and those calculated for soils without considering carbonate content (Section 6.3); the values would be lower than the calculated values, but likely within two orders of magnitude.

Laboratory data (DTNs: GS031208312211.001 [DIRS 171543] and MO0512SPASURFM.002 [DIRS 175955]) report the measured percent calcium carbonate in soil samples collected at Yucca Mountain (Figure 6-11; Table 6-13). Qualitative field estimates, however, are considered more representative than the laboratory measurements of calcium carbonate, which are performed on the less than 2 mm size fraction of the soil samples (NWM-USGS-HP-265, R0, R0-M1, R0-M2). As previously indicated, the measurements would not include carbonate cemented to gravel clasts that are retained on the greater than 2 mm sieves. Figure 6-11 shows the range of carbonate percentages measured in the laboratory for each soil unit, and Table 6-13 compares the laboratory measurements with the field estimates of pedogenic carbonate accumulation. As expected, field estimates are consistently higher than laboratory measurements, yet laboratory measurements accurately reflect the general trend of the qualitative assignments.

Field descriptions (Tables 6-4 and 6-13) indicate that the pedogenic carbonate accumulated in most surficial map units is Stage III or less. Stage III carbonate soils in gravelly deposits have a maximum $CaCO_3$ content of 10% to 25% (Machette 1985 [DIRS 104660], Table 1). Only Soil Unit 1, which is mapped in 8% of the infiltration model area, consistently exhibits a higher stage of development (Stage IV) with regard to carbonate soils (Tables 6-4 and 6-13). Soil Unit 1, which is the oldest of the soil units, also exhibits the most well developed desert pavement (Tables 6-4 and 6-13). It is anticipated that, if measured in the field, the hydraulic parameters for Soil Unit 1 would be less than those developed in Section 6.3. The texture analysis approach that was used does not consider laminar carbonate or cemented carbonate horizons that that can impede groundwater movement. Therefore, it is likely that the downward movement of water in this soil is retarded by the carbonate buildup and desert pavement development. Locally, fractures may enhance the movement through the cemented carbonate horizon, but on balance the downward flow of water is expected to be slowed.



Sources: DTNs: GS031208312211.001 [DIRS 171543], worksheet ‘ALL395’ and MO0512SPASURFM.002 [DIRS 175955], worksheets ‘ALL94’ and ‘ALL295’.

Figure 6-11. Range of Pedogenic Carbonate Measured in Yucca Mountain Soil Units

The hydraulic parameters determined for Soil Unit 2, which constitutes 17% of the model area, are considered to be conservative because, in addition to the argillic horizon development, the unit, with Stage III carbonate soil, could have on the order of 10% to 25% calcium carbonate disseminated in the soil horizons. Also, as previously stated, Stage III carbonate-bearing soils are reported as having about 10% higher water retention properties than sandy loam soils or soils having laminar calcic soils (Duniway et al. 2004 [DIRS 176417]). These soils also have a moderately to well-developed desert pavement, which could also hinder infiltration.

Approximately 60% of the infiltration model area is overlain by Soil Units 3, 4, and 5, which exhibit minimum pedogenic soil and desert pavement development. For these soil units, no to minimal effect due to pedogenic development is expected on the hydraulic parameters developed in Section 6.3. Soil Units 7 and 9, which encompass approximately 8% of the model area, exhibit an increase in clay content through the development of an argillic horizon. This change would have been detected by the particle size distribution data and, thus, changes in hydraulic properties would have been addressed by the methodology discussed in Section 6.3. As previously discussed, Soil Unit 7 does have a moderately to well developed pavement that could result in K_{sat} values lower than those developed with the method used in Section 6.3.

Table 6-13. Percent of Total Samples for Each Soil Unit versus Percent Carbonate Measured in Sample, Compared with Field Observations of Pedogenic Carbonate Development

% Measured $CaCO_3$ →		Stage I	Stage II		Stage III		Stage IV		
		0% to 2%	2% to 5%	5% to 10%	10% to 15%	15% to 25%	25% to 30%	30% to 50%	
Soil Unit	**% Total Area**								**Field Estimate**
1	7.85	0.23	0.27	0.20	0.14	0.08	0.04	0.04	Stages III and IV $CaCO_3$; well developed desert pavement
2	17.38	0.48	0.37	0.11	0.03	0.00	0.00	0.01	Stages II and III $CaCO_3$; moderately to well developed

Table 6-13. Percent of Total Samples for Each Soil Unit versus Percent Carbonate Measured in Sample, Compared with Field Observations of Pedogenic Carbonate Development (Continued)

% Measured $CaCO_3$ →		Stage I	Stage II		Stage III		Stage IV		
		0% to 2%	2% to 5%	5% to 10%	10% to 15%	15% to 25%	25% to 30%	30% to 50%	
Soil Unit	**% Total Area**								**Field Estimate**
									pavement
3	13.06	0.83	0.14	0.03	0.00	0.00	0.00	0.00	Stages I and II $CaCO_3$; pavement weakly developed or absent
4	1.83	0.89	0.04	0.04	0.04	0.00	0.00	0.00	No $CaCO_3$ or pavement development
5	46.06	0.84	0.06	0.10	0.00	0.00	0.00	0.00	Not described
6	4.81	–	–	–	–	–	–	–	Multiple buried $CaCO_3$ soils, poorly to moderately developed pavement
7	1.24	0.72	0.22	0.06	0.00	0.00	0.00	0.00	Not described $CaCO_3$ soils; poorly to well developed pavement
8	0.31	–	–	–	–	–	–	–	Not applicable
9	6.48	0.57	0.17	0.17	0.09	0.00	0.00	0.00	Not described
10	0.98	–	–	–	–	–	–	–	Not applicable

NOTES: Laboratory data are from DTNs: GS031208312211.001 [DIRS 171543], worksheet 'ALL395' and MO0512SPASURFM.002 [DIRS 175955], worksheets 'ALL94' and 'ALL295'. Percent $CaCO_3$ per stage of pedogenic carbonate accumulation is from Machette (1985 [DIRS 104660], Section *Calcic soils of the southwestern United States*, Table 1). Field estimates of pedogenic carbonate stage and desert pavement development are from Table 6-4.

In overall consideration of the effect from pedogenic development on hydraulic parameters of soil units, for use in a replacement infiltration model, the pedogenic products of desert pavement, petrocalcic accumulations, and argillic horizons would slow the movement of infiltrating water through the soil. Therefore, the development of hydraulic properties, based on only particle size distributions, overestimate the rate of infiltration in soil units where these products are present.

6.4.2 Uncertainty Associated with Sampling Methods and Spatial Distribution of Samples

Methods used to collect and analyze samples from Yucca Mountain are outlined in USGS procedures that were in effect during the time that soil textural data were generated (DTNs: GS031208312211.001 [DIRS 171543] and MO0512SPASURFM.002 [DIRS 175955]). The procedures of interest for the purpose of this analysis are the same as those used in the sampling, which are NWM-USGS-GP-17, R1, *Describing and Sampling Soils in the Field*, and NWM-USGS-HP259 R0, R0-M1, R0-M2, *Determination of Bulk Density Using an Irregular Hole Bulk Density Sampler*, along with the procedures used in the determination of the percentages of sand, silt, clay, and rock fragments, which are NWM-USGS-HP-263 R0 and R0-M1, *Particle Size Analysis*.

Sample and analytical methods and procedures used to derive the analogous site database are described by Khaleel and Freeman (1995 [DIRS 175734], Section 2.0). The properties report (Khaleel and Freeman 1995 [DIRS 175734], Section 1) also provides a description of the sites sampled and the type of material found at each location. Samples were collected from boreholes with the use of cable tool and splitspoon coring techniques. Many of the analogous site database samples were collected at depths from approximately 2 to 80 m (Khaleel and Freeman 1995 [DIRS 175734], Appendix A), in contrast to the YMP samples, which were collected at depths of approximately 0 to 20 cm DTNS: MO0512SPASURFM.002 [DIRS 175955], worksheets 'ALL94' and 'ALL295' and GS031208312211.001 [DIRS 171543], worksheet 'ALL395'. Three different methods were used to determine moisture retention data: (1) the hanging water column method, (2) the pressure plate extraction method, and (3) the vapor equilibrium or thermocouple psychrometer method.

Saturated hydraulic conductivities were determined with a constant head permeameter and a falling head permeameter. Particle-size distributions of the analogous site soils and sediments were determined with a hydrometer for fractions of less than 0.075 mm and by dry sieving methods for size fractions of greater than 0.075 mm to less than 2 mm (Khaleel and Freeman 1995 [DIRS 175734], Section 2).

In addition to textural data used to match YMP soils to the analogous site database soils (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B), both DTNs: GS031208312211.001 [DIRS 171543] and MO0512SPASURFM.002 [DIRS 175955] provide sample coordinates (UTM coordinates), sample depth interval (cm), and soil unit designation (Figure 6-1). In addition, DTN: GS000383351030.001 [DIRS 148444] provides particle-size data for Soil Unit 6. These soil units and interval depths were used in the derivation of the soil unit hydraulic parameter statistics (Table 6-7). A detailed discussion of soil properties derivation is provided in Section 6-3. A plot of the sample locations over the infiltration model area shows that there is an inherent uncertainty in the soil properties for areas outside of the sampling area. The majority of the sample locations are clustered in the center of the model grid, while large sections at the edges have no sample locations (Figure 6-1).

Overall, the sample collection methods and laboratory analysis procedures are well documented and reasonable for Yucca Mountain data (DTNs: GS000383351030.001 [DIRS 148444], GS031208312211.001 [DIRS 171543], and MO0512SPASURFM.002 [DIRS 175955]) and for the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B). Yucca Mountain sample locations are clustered in the center of the model area, rather than evenly or randomly distributed over the entire model area. The lack of sample locations at the edges of the model area results in greater uncertainty with increasing distance from the clusters of samples.

6.4.3 Local Nevada Test Site and Nye County Data

Soils local to Yucca Mountain are preferred for the development of soil hydraulic properties for a replacement infiltration model because the hydraulic properties of a given soil type at a given site are the result of the processes and conditions that produced the soil materials at that site. To use soils for deriving hydraulic properties relevant to the Yucca Mountain infiltration grid, the moisture retention curve and applicable parameters, those being the α and n, θ_r, and θ_s (van Genuchten et al. 1991 [DIRS 108810]), along with sufficient textural data consisting of percentages of sand, silt, and clay must be available in the matching or surrogate database; YMP uses the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B). Although two potential sources of local data were identified, they were disqualified because they did not meet the criteria previously discussed. The following description is provided regarding the two data sets that were disqualified.

The two potential sources of local sample data include data collected during the characterization of the Area 3 low-level radioactive waste site and data available for Nye County soils through the USDA Natural Resource Conservation Service (NRCS) online Soil Survey Laboratory Soil Characterization Data Query Interface. The use of the Area 3 characterization data was ruled out early because no clear relationship existed between the textural and moisture retention data samples to enable a clear match to the YMP samples. In addition, the data were received second-hand and could not be qualified without extensive effort.

The NRCS data were well-organized, column-delimited spreadsheets with textural and moisture retention data for samples collected at several locations in Nye County, including a few locations on the Nevada Test Site. The textural and moisture retention data were readily traceable; the moisture retention curve-fitting parameters, however, those being α and n, θ_r, and θ_s (van Genuchten et al. 1991 [DIRS 108810]) were not available. The Nye County moisture retention data provided by the NRCS (USDA 2006 [DIRS 176439]) consisted of moisture content at generally three points: −0.1 bar, −0.33 bar, and −15 bar. An approximate moisture retention curve can be derived from these three points; the resulting curves, however, may not yield dependable results and such an effort is beyond the scope of this analysis.

Overall, the local available data were found to be lacking required qualification or missing important hydraulic parameter or moisture-retention curve-related data, as discussed in this section. The Nye County data (USDA 2006 [DIRS 176439]) were found to be useful in demonstrating reasonableness of the approach as described in Section 6.4.5, but were not sufficient to use as an analog for Yucca Mountain hydraulic parameters.

6.4.4 Uncertainty Associated with Correlation of YMP Soils and Analogous Site Soil and Sediment Hydraulic Parameters

Several attempts have been made to establish a relation between the soil moisture retention curve and readily available soil properties (Cornelis et al. 2001 [DIRS 176383]). Those relationships are referred to as PTFs. Parameters that have been incorporated into PTFs include grain-size distribution, bulk density, porosity, organic matter content, and plasticity index. Some approaches, such as that incorporated into ROSETTA, use a hierarchical scheme. Generally, with these approaches, the more parameters used to develop the PTF, the smaller the uncertainty. The Yucca Mountain data (DTNs: GS000383351030.001 [DIRS 148444], GS031208312211.001 [DIRS 171543], and MO0512SPASURFM.002 [DIRS 175955]) include well-documented grain-size distribution and gravel content (rock fragment content) for most soil samples. Bulk density and porosity data are not complete and, overall, are available for only about 50% of the Yucca Mountain soil samples (DTNs: GS000383351030.001 [DIRS 148444], GS031208312211.001 [DIRS 171543], and MO0512SPASURFM.002 [DIRS 175955]).

The sample matching approach used herein falls under the category of PTF, although the analysis stops short of developing general equations because the model input for stochastic analysis may sample directly from the underlying data, which in this case are the matched sample hydraulic parameter values. The analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) is complete with respect to grain-size distribution and gravel content, but does not include any of the other parameters useful for the development of PTFs, such as bulk density, porosity, organic content, or plasticity index. The soils and sediments identified in the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) were collected at Hanford, an arid region of eastern Washington. The soils at Hanford have developed under arid climatic conditions similar to those at Yucca Mountain. The average annual precipitation at Hanford is about 17.3 cm/yr (DOE 2001 [DIRS 177079], Section 3.2) compared to about 12.5 cm/yr for Yucca Mountain (BSC 2004 [DIRS 169734], Section 3.42). Hanford sediments have organic carbon content below 0.5 wt% (Truex et al. 2001 [DIRS 177078], Section 2.3.1.2). Organic carbon content in agricultural areas of Nye County range from about 0.006% to 0.70% (USDA 2006 [DIRS 176439]).

The soils at Hanford contain less organic material than soils developed under wetter conditions, which is also true of the soils at Yucca Mountain. The soil depositional processes at Yucca Mountain compared to those at Hanford include some differences that can contribute to differences in grain shape and soil structure. Large-scale fluvial processes dominate Hanford soil and sediments resulting in more-rounded particles and single-grain structure. Small-scale fluvial processes and eolian (Soil Unit 6) are the dominant processes at Yucca Mountain, resulting in less-rounded particles with more angular fragments (Section 6.2). Soils of fluvial origin associated with Soil Units 1 through 4 (stream and alluvial fan material) cover over 40% of the infiltration model area. There is an eolian component that has accumulated on these surfaces through time, which is concentrated in the upper 0.5 to 1 m of the soil profile. Deposits representing eolian source material are mapped over only 4.8% of the area (Soil Unit 6).

The dominant surficial deposit (54% of the model area; Soil Units 5, 7, and 9) is colluvium. The colluvium consists of rock fragments of parent material that have been separated from the underlying intact bedrock through weathering processes. Colluvium, however, by definition, does not remain in situ, but moves or has moved, or both, downslope through gravitational processes. The fine-grained component of colluvial soils is interpreted to be due to the influx of eolian material. There are depositional mode differences between the YMP soils and Hanford soils and sediments; the differences in the associated hydraulic parameters, however, are not quantified because there are no site-specific hydraulic data for Yucca Mountain. Such differences contribute to an overall uncertainty, captured by the development of descriptive statistics for each hydraulic parameter, which include the parameter mean and standard deviations.

Overall, the literature review suggests that the matching approach, using the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B), would be less uncertain if additional data, such as bulk density, were available for Yucca Mountain and for Hanford.

6.4.5 Corroboration of Yucca Mountain Soil Parameters Derived from the Analogous Database with Two Alternate Pedotransfer Functions

An analysis was performed with the purpose of comparing the Yucca Mountain hydraulic soils properties generated with the Hanford data set against two other PTF methods (Appendix B). One of the PTF methods is outlined by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and later implemented by Carsel and Parrish (1988 [DIRS 147295]). The second method utilizes the ROSETTA program and database, a neural network-based model; a description of the algorithms and neural network methodology is provided by Schaap et al. (1998 [DIRS 177199] and 2001 [DIRS 176006]).

The purpose of this analysis is to provide a direct comparison between different PTF methods to show both a variation among hydraulic parameters generated by different PTF and that the method outlined in this analysis is reasonable when compared to other methods. The analysis was performed using the PTF methods to derive the hydraulic properties for each of the Yucca Mountain samples, similar to the method of matching the Yucca Mountain samples to the analogous site database and assigning a Yucca Mountain sample the same hydraulic properties as a matched Hanford sample (Section 6.3).

After deriving the hydraulic properties, using the two PTF methods, the hydraulic properties were organized into the same soil unit groups as was done with the analogous site data to include the soil units of Soil Unit 1, Soil Units 2 and 6, Soil Units 3 and 4, and Soil Units 5, 7, and 9. The descriptive statistics and standard errors were computed for these groups and compared to the descriptive statistics of the Hanford soil properties.

The method outlined by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) is performed with a multiple regression model of the form:

$$\begin{aligned}\ln(K_{sat}),\ \theta_r,\ \ln(\alpha^{-1}),\ \ln(n-1) = [&c_0 + c_1S + c_2C + c_3\theta_s + c_{11}S^2 + c_{22}C^2 + c_{33}\theta_s^{\,2} + \\ &c_{12}S\%C + c_{13}S\theta_s + c_{23}C\theta_s + c_{112}S^2C + c_{223}C^2\theta_s + \\ &c_{113}S^2\theta_s + c_{122}SC^2 + c_{233}C\theta_s^{\,2} + c_{1133}S^2\theta_s^{\,2} + c_{2233}C^2\theta_s^{\,2}]\end{aligned}$$

where

S = percent sand ($5<S<70$)

C = percent clay ($5<C<60$)

θ_s = total saturated water content (cm^3/cm^3)

K_{sat} = saturated hydraulic conductivity (cm/hr)

θ_r = residual water content (cm^3/cm^3)

α = empirical van Genuchten et al. (1991 [DIRS 108810]) curve fitting constant (1/cm)

n = empirical van Genuchten et al. (1991 [DIRS 108810]) curve fitting constant (unitless)

c = coefficients

The coefficient, c, values (Table 6-14) were originally taken from Carsel and Parrish (1988 [DIRS 147295], Figure 1). Several errors were identified, however, associated with θ_r and ln(α-1) (Carsel and Parrish 1988 [DIRS 147295], Figure 1). Thus, the errors were replaced with correct coefficients from NUREG/CR-6565 (Meyer 1997 [DIRS 176004], p. 5). Soil parameters calculated using the Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) regression equation are limited to a percent sand range of 5% to 70%. Soil samples with sand ranges greater than 70% must be corrected using the method outlined by Cronican and Gribb (2004 [DIRS 177039]).

Following the derivation of soil properties (Rawls and Brakensiek 1985 [DIRS 177045]) and, as applicable, the correction by Cronican and Gribb (2004 [DIRS 177039]), soil properties were corrected for Yucca Mountain gravel content as was done with the analogous site data (Section 6.3.3). The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated (Appendix B and DTN: MO0608SPAPEDOT.000) for each of the hydraulic parameters (Table 6-15) for alternate soil group 2 (Section 6.3.4.3) and the soil units in alternate soil group 1 (Section 6.3.4.2).

The analysis using ROSETTA (Appendix B) was performed by entering Yucca Mountain soil textures and bulk densities, when available, into the software program through a text input file for each Yucca Mountain sample used in the base case analysis. Output from ROSETTA consisted of the saturated hydraulic conductivity (K_{sat}), van Genuchten parameters α and n, θ_r, and θ_s (van Genuchten et al. 1991 [DIRS 108810]). The gravel corrections were performed for K_{sat}, θ_r, and θ_s in the same manner as the analogous site data (Section 6.3.3). The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated (DTN: MO0608SPAPEDOT.000) for each of the hydraulic parameters (Table 6-16) for alternate soil group 2 (Section 6.3.4.3) and the soil units in alternate soil group 1 (Section 6.3.4.2).

The comparison analysis was performed for a group including all base case soil units, as well as the alternate groups, those being Soil Unit 1, Soil Units 2 and 6, Soil Units 3 and 4, and Soil Units 5, 7, and 9. Figures 6-12 to 6-19 show the comparison of the mean soil parameter values. The analysis files are available in DTN: MO0608SPAPEDOT.000.

Figures 6-12 and 6-13 show that FC moisture contents derived from the analogous site database method are slightly larger than the other two methods. This increase in moisture content is also manifested in the WHC based on −0.10 and −0.33 bar (Figures 6-15 and 6-16) and θ_s. Moisture contents calculated with ROSETTA are generally lower than those calculated with the other two methods.

Soils from temperate and subtropical climates and agricultural soils generally have larger holding capacities compared to desert soils and it is likely that the PTFs of the Rawls and Brakensiek method (Rawls and Brakensiek 1985 [DIRS 177045]) and of ROSETTA are based on such soils. Thus, the greater WHC calculated using the analogous site database compared to WHC calculated with Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and those of ROSETTA is unexpected.

This result is consistent with a recharge study at the Glassboro Study Area, New Jersey, by the USGS in which it found that ROSETTA lead to unreasonably high recharge estimates, primarily due to the over-prediction of saturated hydraulic conductivity (USGS 2003 [DIRS 177192], p. 2). The study used data from six locations in southern New Jersey that appear to have steady-state flow conditions and five hydraulic property prediction and parameterization techniques were evaluated for recharge estimation. The unsaturated zone at the Glassboro Study Area, New Jersey, is mainly sand to sandy loam in texture. It is not clear why ROSETTA may be over-predicting $K_{sat;}$ the same study found that water retention was predicted relatively well by ROSETTA (USGS 2003 [DIRS 177192], p. 2). Figures 6-18 and 6-19 provide comparisons between the three methods based on arithmetic mean values and geometric mean values of K_{sat}, respectively. When comparing the results based on the arithmetic mean values, the large values dominate and the three methods appear to result in very similar K_{sat} values. Small K_{sat} values dominate with comparison of the geometric mean. This comparison reveals that the analogous site method and the Rawls and Brakensiek method (Rawls and Brakensiek 1985 [DIRS 177045]) have good agreement and, as previously noted, the ROSETTA results are consistently larger; the smaller the bar the larger the K_{sat} value.

Table 6-14. Rawls and Brakensiek Regression Constants

Term	Natural Log Saturated Hydraulic Conductivity (K_{sat}) Ln[cm/hr]	Residual Water Content (θr) [cm^3/cm^3]	Natural Log (1/α) Ln[cm]	Natural Log N −dimensionless
(Constant)	–8.96847	–0.0182482	5.3396738	–0.7842831
S	0	0.00087269	0	0.0177544
C	–0.028212	0.00513488	0.1845038	0
θs	19.52348	0.02939286	–2.48394546	–1.062498
S^2	0.00018107	0	0	−5.30E-05
C^2	–0.0094125	–0.00015395	–0.00213853	–0.00273493
θ_s^2	−8.395215	0	0	1.11134946
SC	0	0	0	0
$S\theta_s$	0.077718	–0.0010827	–0.0435649	–0.03088295
$C\theta_s$	0	0	–0.61745089	0
S^2C	0.0000173	0	–1.282E-05	–2.35E-06
$C^2\theta_s$	0.02733	0.00030703	0.00895359	0.00798746
$S^2\theta_s$	0.001434	0	–7.2472E-04	0
SC^2	–0.0000035	0	5.40E-06	0
$C\theta_s^2$	0	−0.0023584	0.5002806	−0.00674491
$S^2\theta_s^2$	–0.00298	0	0.00143598	2.6587E-04
$C^2\theta_s^2$	–0.019492	–0.00018233	–0.00855375	–0.00610522

Source: Carsel and Parrish 1988 [DIRS 147295], Figure 1.

NOTE: NOTE: Corrected coefficients for θ_r and 1/α are from NUREG/CR-6565 (Meyer 1997[DIRS 176004], p. 5).

Table 6-15. Summary of Soil Hydraulic Parameter and Statistics Estimated with the Rawls and Brakensiek Method for Alternate Soil Groups 1 and 2

Statistical Parameters	PWP at –60 bar (–61,200 cm), cm^3/cm^3	Moisture Content at –0.10 bar (–102 cm), cm^3/cm^3	Moisture Content at –0.33 bar (–336.6 cm), cm^3/cm^3	WHC Based on –0.10 bar FC, cm^3/cm^3	WHC Based on –0.33 bar FC	Saturated Hydraulic Conductivity, cm/sec	Ln(Saturated Hydraulic Conductivity), cm/sec	θ_s, cm^3/cm^3
Alternate Soil Group 2 (One Soil Unit)[a]								
Mean	0.039	0.103	0.076	0.064	0.037	3.98E-04	–9.417	0.186
Standard Deviation	0.018	0.049	0.038	0.035	0.023	1.45E-03	1.648	0.083
Median	0.037	0.103	0.075	0.061	0.034	7.62E-05	–9.483	0.181
Max	0.101	0.243	0.187	0.219	0.151	1.52E-02	–4.187	0.410
Min	0.005	0.011	0.008	0.005	0.003	4.28E-06	–12.363	0.027
Count	206	206	206	206	206	206	206	206
Standard Error	0.001	0.003	0.003	0.002	0.002	1.01E-04	0.115	0.006
Soil Unit 1 from Alternate Soil Group 1[b]								
Mean	0.060	0.158	0.119	0.098	0.059	1.93E-04	–9.337	0.270
Standard Deviation	0.019	0.035	0.031	0.019	0.014	2.09E-04	1.462	0.057
Median	0.058	0.160	0.117	0.099	0.061	1.35E-04	–8.917	0.257
Max	0.101	0.235	0.187	0.134	0.087	7.40E-04	–7.209	0.407
Min	0.026	0.087	0.057	0.061	0.031	4.93E-06	–12.221	0.191
Count	24	24	24	24	24	24	24	24
Standard Error	0.004	0.007	0.006	0.004	0.003	4.26E-05	0.298	0.012
Soil Unit 2-6 from Alternate Soil Group 1[c]								
Mean	0.046	0.134	0.096	0.088	0.050	1.93E-04	–9.087	0.235
Standard Deviation	0.012	0.037	0.027	0.029	0.019	2.30E-04	1.053	0.061
Median	0.044	0.140	0.097	0.087	0.051	1.10E-04	–9.119	0.242
Max	0.068	0.208	0.152	0.140	0.085	8.21E-04	–7.105	0.319
Min	0.031	0.062	0.045	0.031	0.014	1.70E-05	–10.985	0.107
Count	17	17	17	17	17	17	17	17
Standard Error	0.003	0.009	0.007	0.007	0.005	5.57E-05	0.255	0.015

Table 6-15. Summary of Soil Hydraulic Parameter and Statistics Estimated with the Rawls and Brakensiek Method for Alternate Soil Groups 1 and 2 (Continued)

Statistical Parameters	**PWP at –60 bar (–61,200 cm), cm^3/cm^3**	**Moisture Content at –0.10 bar (–102 cm), cm^3/cm^3**	**Moisture Content at –0.33 bar (–336.6 cm), cm^3/cm^3**	**WHC Based on –0.10 bar FC, cm^3/cm^3**	**WHC Based on –0.33 bar FC**	**Saturated Hydraulic Conductivity, cm/sec**	**Ln(Saturated Hydraulic Conductivity), cm/sec**	**θ_s, cm^3/cm^3**
Soil Unit 3-4 from Alternate Soil Group 1[d]								
Mean	0.029	0.067	0.050	0.039	0.021	4.83E-04	–9.429	0.134
Standard Deviation	0.015	0.037	0.028	0.023	0.014	1.49E-03	1.768	0.065
Median	0.026	0.061	0.044	0.034	0.019	6.43E-05	–9.652	0.132
Max	0.072	0.174	0.133	0.110	0.065	1.25E-02	–4.385	0.291
Min	0.005	0.011	0.008	0.005	0.003	8.22E-06	–11.709	0.027
Count	91	91	91	91	91	91	91	91
Standard Error	0.002	0.004	0.003	0.002	0.001	1.56E-04	0.185	0.007
Soil Unit 5-7-9 from Alternate Soil Group 1[e]								
Mean	0.043	0.115	0.084	0.072	0.042	1.94E-04	–9.562	0.203
Standard Deviation	0.013	0.034	0.026	0.024	0.015	3.19E-04	1.450	0.069
Median	0.040	0.111	0.081	0.069	0.041	5.12E-05	–9.879	0.194
Max	0.078	0.203	0.156	0.128	0.079	2.18E-03	–6.129	0.410
Min	0.021	0.058	0.040	0.027	0.014	6.01E-06	–12.023	0.086
Count	73	73	73	73	73	73	73	73
Standard Error	0.002	0.004	0.003	0.003	0.002	3.73E-05	0.170	0.008

Sources: Rawls and Brakensiek 1985 [DIRS 177045].

[a] DTN: MO0608SPAPEDOT.000, *AllSoilUnits_Method-Verification_August31_2006.xls*, worksheet ‘AllSoilUnits Statistics’.
[b] DTN: MO0608SPAPEDOT.000, *SoilUnit1_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnit1 Statistics’.
[c] DTN: MO0608SPAPEDOT.000, *SoilUnit2-6_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnits2-6 Statistics’.
[d] DTN: MO0608SPAPEDOT.000, *SoilUnit3-4_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnits3-4 Statistics’.
[e] DTN: MO0608SPAPEDOT.000, *SoilUnit5-7-9_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnits5-7-9 Statistics’.

FC = field capacity; PWP = permanent wilting point; WHP = water holding capacity.

Table 6-16. Summary of Soil Hydraulic Parameter and Statistics Estimated with ROSETTA for Alternate Soil Groups 1 and 2

Statistical Parameters	PWP at –60 bar (–61,200 cm), cm^3/cm^3	Moisture Content at –0.10 bar (–102 cm), cm^3/cm^3	Moisture Content at –0.33 bar (–336.6 cm), cm^3/cm^3	WHC Based on –0.10 bar FC, cm^3/cm^3	WHC Based on –0.33 bar FC	Saturated Hydraulic Conductivity, cm/sec	Ln(Saturated Hydraulic Conductivity), cm/sec	θ_s, cm^3/cm^3
Alternate Soil Group 2 (One Soil Unit)[a]								
Mean	0.026	0.093	0.063	0.067	0.037	4.88E-04	–8.042	0.176
Standard Deviation	0.015	0.066	0.049	0.053	0.035	5.11E-04	0.926	0.084
Median	0.022	0.079	0.050	0.055	0.027	3.12E-04	–8.072	0.166
Max	0.083	0.328	0.240	0.284	0.196	3.72E-03	–5.594	0.378
Min	0.002	0.004	0.002	0.002	0.000	2.10E-05	–10.772	0.015
Count	424	424	424	424	424	424	424	424
Standard Error	0.001	0.003	0.002	0.003	0.002	2.48E-05	0.045	0.004
Soil Unit 1 from Alternate Soil Group 1[b]								
Mean	0.030	0.119	0.082	0.089	0.052	4.46E-04	–8.012	0.201
Standard Deviation	0.020	0.088	0.065	0.070	0.047	3.68E-04	0.816	0.099
Median	0.025	0.110	0.072	0.085	0.043	3.50E-04	–7.957	0.212
Max	0.083	0.328	0.240	0.284	0.196	2.26E-03	–6.091	0.378
Min	0.004	0.011	0.007	0.005	0.000	2.65E-05	–10.539	0.035
Count	84	84	84	84	84	84	84	84
Standard Error	0.002	0.010	0.007	0.008	0.005	4.02E-05	0.089	0.011
Soil Unit 2-6 from Alternate Soil Group 1[c]								
Mean	0.028	0.097	0.065	0.070	0.038	6.53E-04	–7.781	0.187
Standard Deviation	0.016	0.071	0.052	0.057	0.038	6.54E-04	0.980	0.092
Median	0.026	0.084	0.048	0.051	0.021	4.10E-04	–7.799	0.173
Max	0.069	0.267	0.194	0.213	0.132	3.40E-03	–5.685	0.364
Min	0.002	0.004	0.002	0.002	0.000	2.20E-05	–10.723	0.015
Count	112	112	112	112	112	112	112	112
Standard Error	0.001	0.007	0.005	0.007	0.005	6.18E-05	0.093	0.009

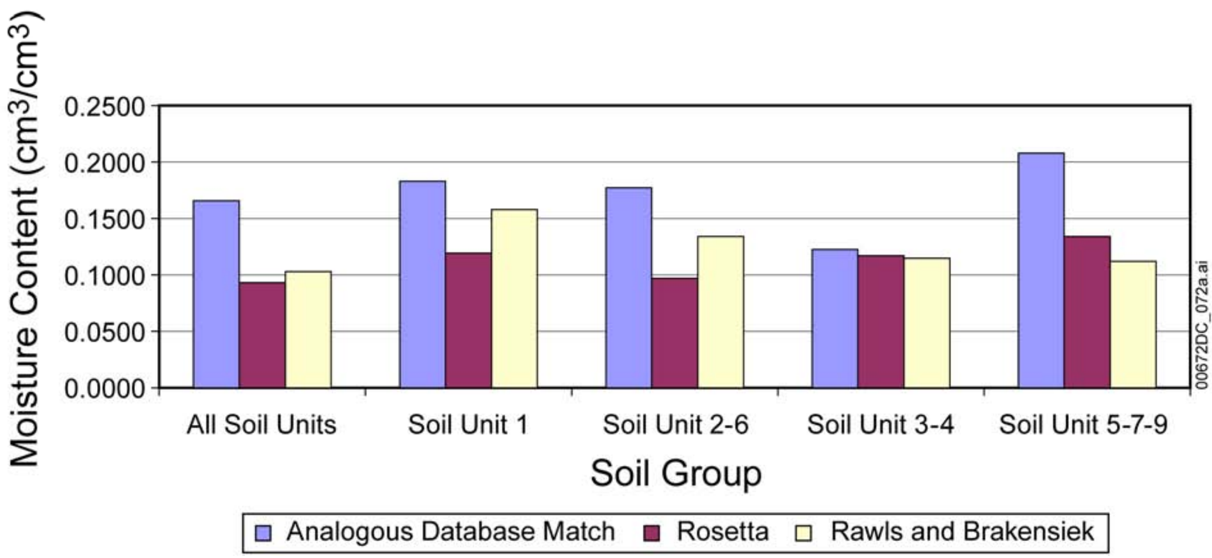
Table 6-16. Summary of Soil Hydraulic Parameter and Statistics Estimated with ROSETTA for Alternate Soil Groups 1 and 2 (Continued)

Statistical Parameters	**PWP at −60 bar (−61,200 cm), cm^3/cm^3**	**Moisture Content at −0.10 bar (−102 cm), cm^3/cm^3**	**Moisture Content at −0.33 bar (−336.6 cm), cm^3/cm^3**	**WHC Based on −0.10 bar FC, cm^3/cm^3**	**WHC Based on −0.33 bar FC**	**Saturated Hydraulic Conductivity, cm/sec**	**Ln(Saturated Hydraulic Conductivity), cm/sec**	**θ_s, cm^3/cm^3**
Soil Unit 3-4 from Alternate Soil Group 1[d]								
Mean	0.019	0.059	0.038	0.040	0.019	5.43E-04	−7.892	0.140
Standard Deviation	0.011	0.040	0.028	0.031	0.020	5.19E-04	0.890	0.069
Median	0.017	0.048	0.029	0.034	0.013	3.50E-04	−7.957	0.130
Soil Unit 3-4 from Alternate Soil Group 1 (Continued)[d]								
Max	0.055	0.188	0.141	0.140	0.088	3.00E-03	−5.809	0.355
Min	0.003	0.007	0.005	0.002	0.000	2.10E-05	−10.772	0.027
Count	141	141	141	141	141	141	141	141
Standard Error	0.001	0.003	0.002	0.003	0.002	4.37E-05	0.075	0.006
Soil Unit 5-7-9 from Alternate Soil Group 1[e]								
Mean	0.030	0.117	0.082	0.087	0.052	2.23E-04	−8.660	0.194
Standard Deviation	0.010	0.043	0.031	0.034	0.022	1.51E-04	0.763	0.059
Median	0.029	0.113	0.080	0.081	0.049	1.82E-04	−8.614	0.187
Max	0.058	0.254	0.176	0.196	0.117	7.64E-04	−7.177	0.371
Min	0.004	0.019	0.012	0.015	0.008	2.66E-05	−10.533	0.039
Count	87	87	87	87	87	87	87	87
Standard Error	0.001	0.005	0.003	0.004	0.002	1.62E-05	0.082	0.006

Sources: Schaap 2001 [DIRS 176006].

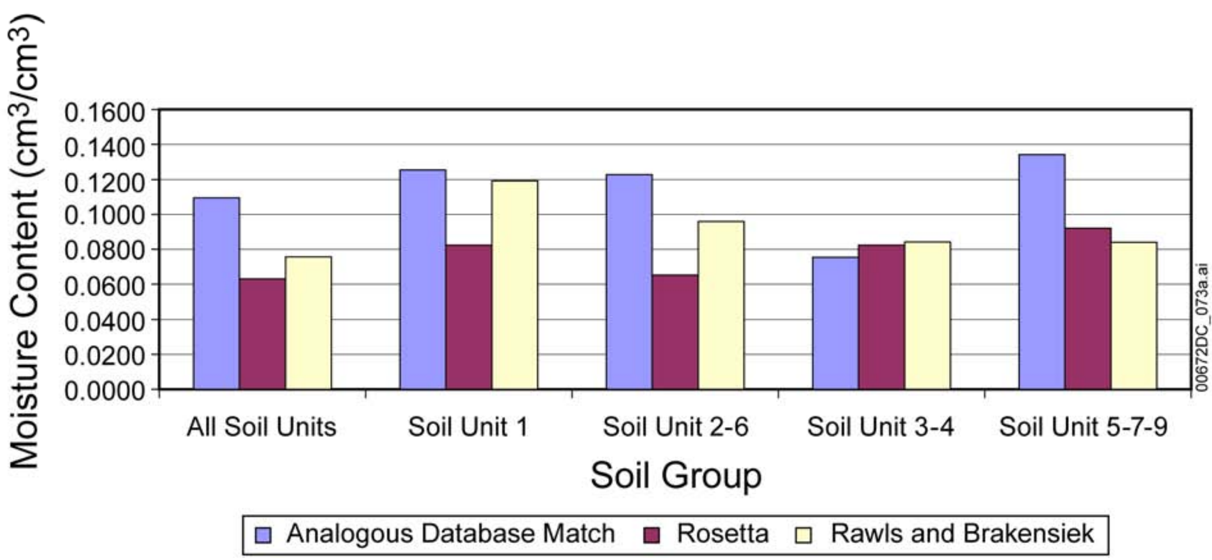
[a] DTN: MO0608SPAPEDOT.000, *AllSoilUnits_Method-Verification_August31_2006.xls*, worksheet ‘AllSoilUnits Statistics’.
[b] DTN: MO0608SPAPEDOT.000, *SoilUnit1_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnit1 Statistics’.
[c] DTN: MO0608SPAPEDOT.000, *SoilUnit2-6_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnits2-6 Statistics’.
[d] DTN: MO0608SPAPEDOT.000, *SoilUnit3-4_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnits3-4 Statistics’.
[e] DTN: MO0608SPAPEDOT.000, *SoilUnit5-7-9_Method-Corroboration_August31_2006.xls*, worksheet ‘SoilUnits5-7-9 Statistics’.

FC = field capacity; PWP = permanent wilting point; WHP = water holding capacity.



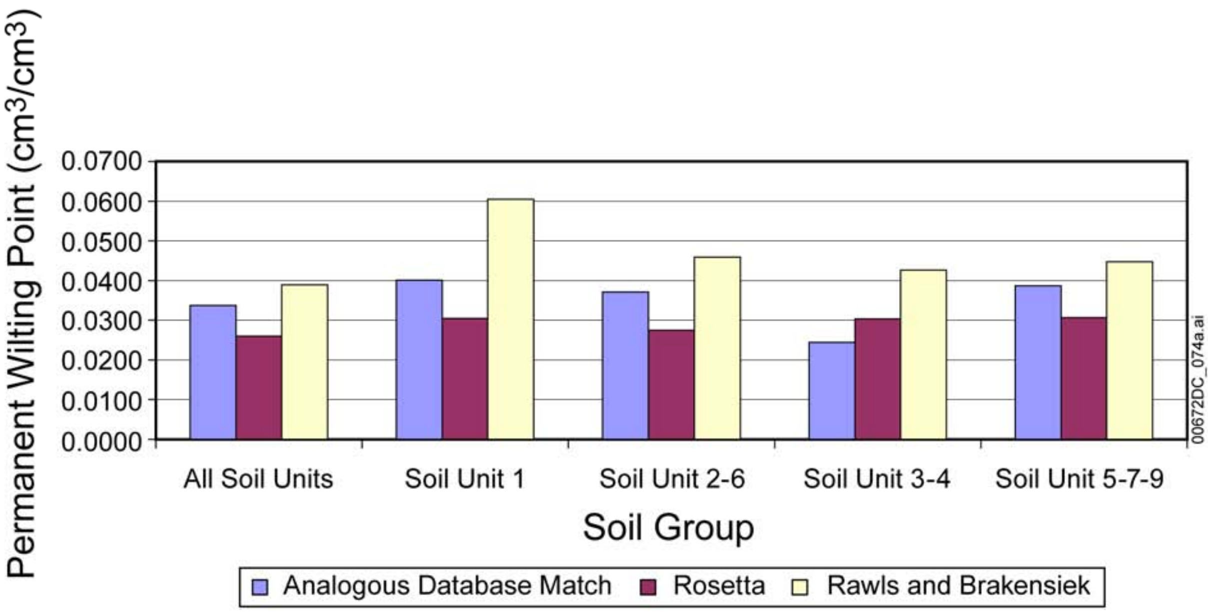
Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_August31_2006.xls*, worksheet 'CompareMeans'.

Figure 6-12. Mean Moisture Content Values at –0.10 Bar (–102 cm) for Three Pedotransfer Function Methods Using Yucca Mountain Data



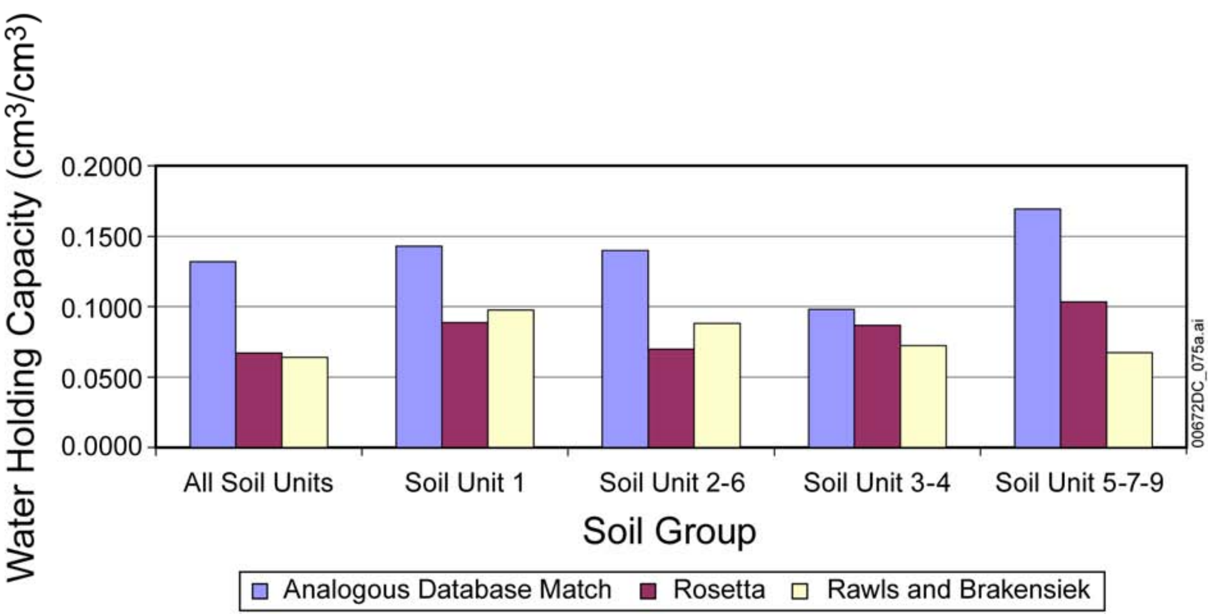
Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_ August31_2006.xls*, worksheet 'CompareMeans'.

Figure 6-13. Mean Moisture Content Values at –0.33 Bar (–336.6 cm) for Three Pedotransfer Function Methods Using Yucca Mountain Data



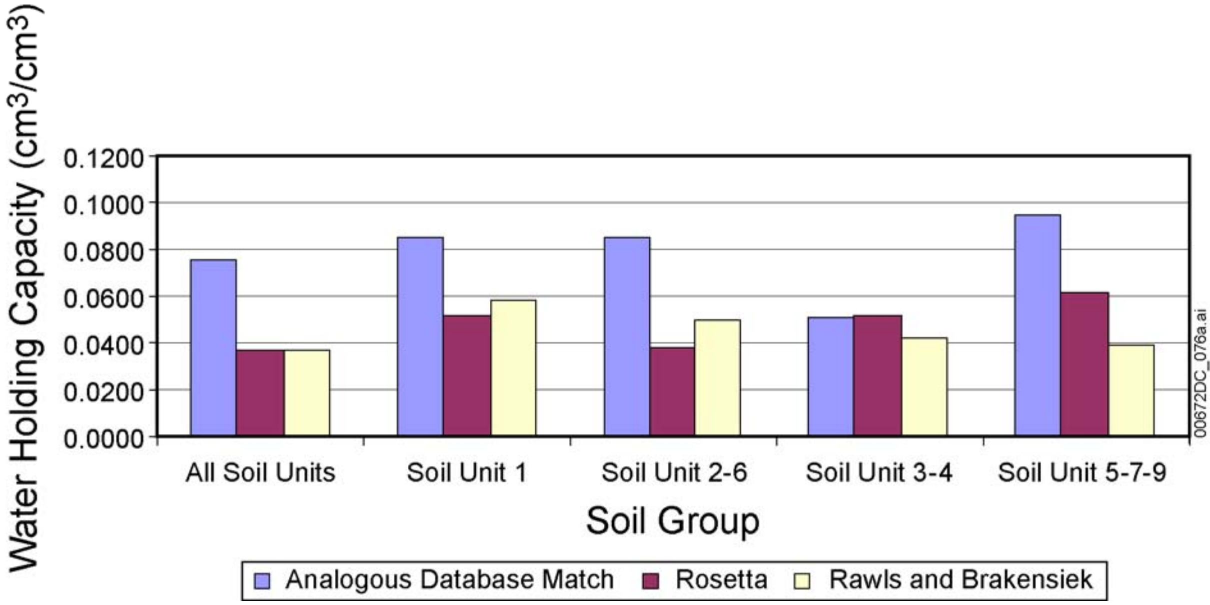
Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_ August31_2006.xls*, worksheet 'CompareMeans'.

Figure 6-14. Mean Permanent Wilting Point at –60 Bar for Three Pedotransfer Function Methods Using Yucca Mountain Data



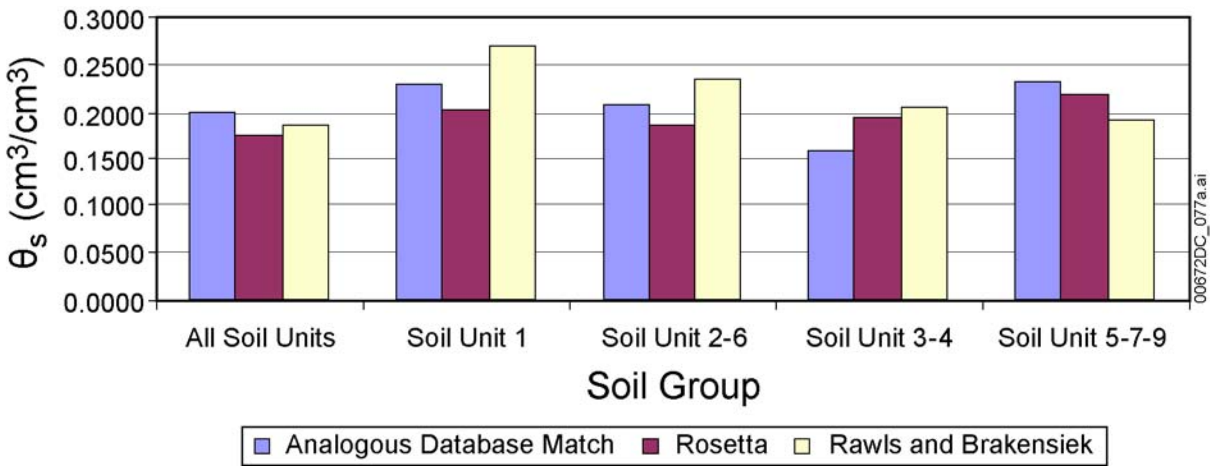
Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_August31_2006.xls*, worksheet 'CompareMeans'.

Figure 6-15. Mean Water Holding Capacity at –0.10 Bar (–102 cm) Field Capacity for Three Pedotransfer Function Methods Using Yucca Mountain Data



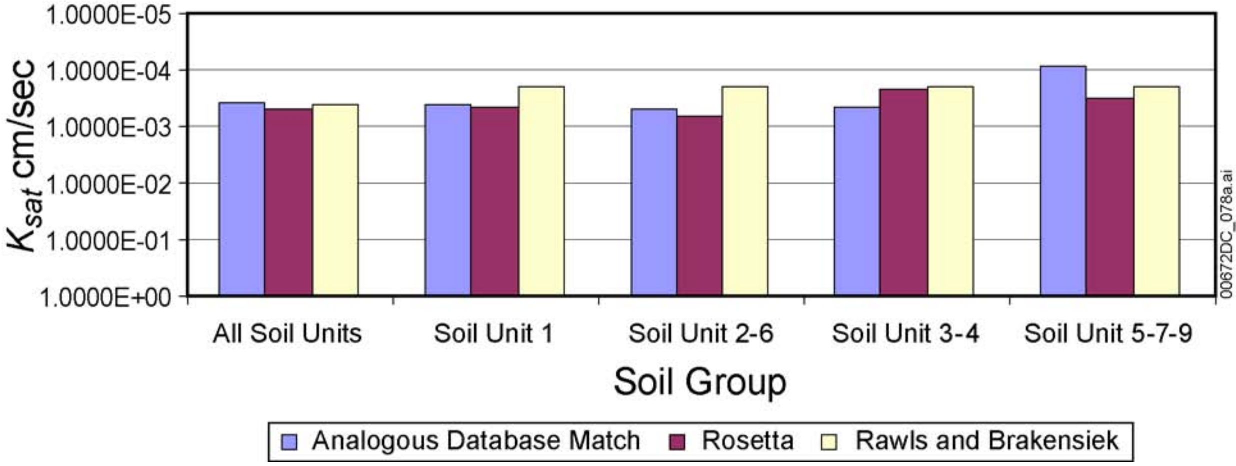
Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_August31_2006.xls*, worksheet 'CompareMeans'.

Figure 6-16. Mean Water Holding Capacity at –0.33 Bar (–336.6 cm) Field Capacity for Three Pedotransfer Function Methods Using Yucca Mountain Data



Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_August31_2006.xls*, worksheet 'CompareMeans'.

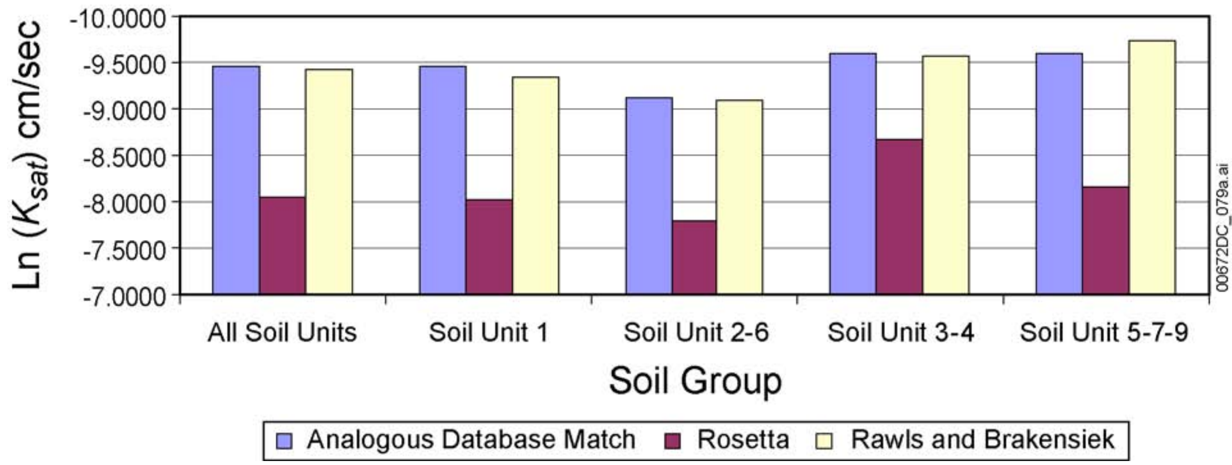
Figure 6-17. Mean θ_S for Three Pedotransfer Function Methods Using Yucca Mountain Data



Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_August31_2006.xls*, worksheet 'CompareMeans'.

NOTES: The y-axis is inverted such that the smaller values are at the top of the Figure. Means are based on arithmetic averages with emphasize any large values in the data set.

Figure 6-18. Mean K_{sat} for Three Pedotransfer Function Methods Using Yucca Mountain Data



Source: DTN: MO0608SPAPEDOT.000, *Summary_MethodCorroboration_August31_2006.xls*, worksheet 'CompareMeans'.

NOTES: The y-axis is inverted such that the smaller values are at the top of the figure. Means are based on the geometric means, which emphasizes any small values in the data set.

Figure 6-19. Mean Ln (K_{sat}) for Three Pedotransfer Function Methods Using Yucca Mountain Data

6.4.6 Corroboration of Nye County Soil Parameters Derived from the Analogous Database with Two Alternate Pedotransfer Functions

The reasonableness of the matching approach is tested graphically using data published by the USDA for Nye County, Nevada (USDA 2006 [DIRS 176439]). Relevant Nye County data include grain-size distribution, rock fragment content, bulk density, and varying amounts of moisture content data. The initial criteria for selecting Nye County data were based on available soil texture and available moisture content data. The soil hydraulic properties were derived using soil textural data of percentages of silt, sand, and clay, and rock fragment content, from the

Nye County data in the same manner used to derive soil hydraulic properties for the Yucca Mountain data using the analogous site database (Khaleel and Freeman 1995 [DIRS 175734]) (Section 6.3). The Nye County samples used in the analysis are listed in Table 6-17 with corresponding percent sand, silt, and clay, which determines the soil texture. The hydraulic properties resulting from the match with the analogous site database (Khaleel and Freeman 1995 [DIRS 175734]) are listed in Table 6-18.

Table 6-17. Nye County Soils Selected for Comparison

Nye County Layer (Sample) Identification	Soil Texture Class	Sand	Silt	Clay
73C00274	Sand	93%	3%	4%
73C00275	Loamy sand	87%	6%	7%
73C00276	Sandy loam	77%	14%	9%
73C00277	Sandy loam	72%	15%	12%
73C00278	Sand	92%	3%	5%
73C00279	Sand	95%	2%	4%
73C00280	Sand	91%	4%	5%
73C00284	Sand	87%	9%	3%
73C00285	Sandy loam	74%	20%	6%
73C00286	Sandy loam	71%	12%	18%
73C00287	Sandy clay	49%	12%	39%
73C00288	Sandy clay loam	58%	12%	30%
73C00289	Sandy loam	63%	19%	18%
73C00290	Loamy sand	81%	13%	7%
73C00298	Loamy sand	87%	10%	4%
73C00299	Sandy loam	56%	37%	7%
73C00300	Sandy clay loam	52%	21%	27%
73C00301	Clay	44%	7%	49%
73C00302	Sandy clay loam	52%	14%	35%
73C00306	Sandy clay loam	55%	24%	21%
73C00307	Sandy clay loam	60%	14%	26%
73C00308	Sandy loam	69%	13%	18%
73C00309	Sand	92%	5%	4%
73C00310	Sandy loam	80%	8%	12%
73C00311	Sand	91%	3%	6%
73C00312	Sand	93%	3%	4%
73C00313	Sand	94%	3%	3%
73C00323	Clay loam	36%	34%	30%
73C00324	Clay	29%	28%	44%
73C00325	Clay	14%	30%	56%
73C00326	Clay	12%	38%	51%
73C00327	Silty clay	5%	45%	50%
73C00328	Clay	17%	40%	43%
73C00329	Silty clay loam	15%	47%	38%
73C00330	Silty clay loam	6%	57%	37%

Table 6-17. Nye County Soils Selected for Comparison (Continued)

Nye County Layer (Sample) Identification	Soil Texture Class	Sand	Silt	Clay
73C00331	Silty clay	6%	50%	44%
73C00332	Silty clay	4%	51%	45%
73C00335	Sandy loam	74%	21%	5%
73C00336	Sandy loam	73%	16%	11%
73C00337	Loamy sand	79%	12%	9%
73C00338	Sandy clay	51%	12%	37%
73C00339	Sandy clay	56%	8%	36%
73C00340	Sandy clay loam	63%	8%	29%
73C00341	Sandy loam	66%	15%	20%
73C00342	Loamy sand	83%	10%	7%
73C00343	Loamy sand	85%	8%	7%
73C00344	Sand	93%	3%	4%
73C00353	Clay	50%	31%	20%
73C00354	Clay	43%	32%	25%
73C00355	Clay	47%	32%	21%
73C00356	Clay	42%	38%	21%
73C00357	Loam	23%	43%	34%
73C00359	Clay Loam	28%	37%	35%
78P03301	Sandy loam	60%	31%	9%
78P03303	Sandy loam	63%	29%	8%
78P03306	Sandy loam	75%	19%	7%
78P03308	Sandy loam	59%	29%	12%
78P03310	Sandy loam	61%	28%	12%
78P03313	Sandy loam	70%	19%	12%
80P00924	Loamy sand	80%	13%	7%
87P03200	Sandy loam	72%	24%	4%
87P03201	Sandy loam	65%	26%	9%
87P03202	Sandy loam	66%	24%	10%
87P03203	Sandy loam	65%	28%	7%
87P03204	Sandy loam	56%	34%	10%
87P03205	Sandy loam	66%	27%	6%
92P03331	Sand	87%	11%	2%
92P03332	Sandy loam	64%	29%	7%
92P03335	Loamy sand	77%	16%	7%
92P03339	Sandy loam	75%	18%	7%
92P03340	Loamy sand	80%	15%	5%
92P03344	Loamy sand	79%	18%	3%
92P03345	Sandy loam	76%	17%	8%
92P03349	Loamy sand	83%	15%	2%
92P03350	Sand	89%	7%	5%

Table 6-17. Nye County Soils Selected for Comparison (Continued)

Nye County Layer (Sample) Identification	Soil Texture Class	Sand	Silt	Clay
92P03351	Sandy clay loam	69%	12%	20%
92P03352	Sandy loam	78%	8%	14%
92P03353	Loamy sand	84%	6%	10%

Sources: USDA 2006 [DIRS 176439]; USDA 1999 [DIRS 152585], Exhibit 618-8;
DTN: MO0608SPANYECT.000, *NyeCountyInputData.txt*.

Table 6-18. Textural Match of Hanford Soil Samples to Nye County Soil Samples and Associated Hydraulic Parameter Values

Nye County Soil Sample ID	Hanford Site Soil Sample ID	Saturated Hydraulic Conductivity, K_{sat}, cm/sec	θ_r,	θ_s,	α	n
73C00274	3-0682	4.57E-05	0.05	0.43	0.013	2.086
73C00275	4-0973	1.27E-04	0.02	0.35	0.017	2.009
73C00276	5-0005	6.70E-05	0.04	0.39	0.007	2.243
73C00277	No Match	NA	NA	NA	NA	NA
73C00278	5A	5.73E-04	0.02	0.41	0.148	1.309
73C00279	241-AP-2	5.97E-04	0.10	0.52	0.031	3.087
73C00280	5A	5.73E-04	0.02	0.41	0.148	1.309
73C00284	4-0973	1.27E-04	0.02	0.35	0.017	2.009
73C00285	5-0005	6.70E-05	0.04	0.39	0.007	2.243
73C00286	No Match	NA	NA	NA	NA	NA
73C00287	4-1058	NA	0.10	0.57	0.003	1.527
73C00288	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00289	No Match	NA	NA	NA	NA	NA
73C00290	241-AP-6	8.60E-05	0.07	0.40	0.005	1.948
73C00298	4-0973	1.27E-04	0.02	0.35	0.017	2.009
73C00299	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00300	4-1058	NA	0.10	0.57	0.003	1.527
73C00301	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00302	4-1058	NA	NA	NA	NA	NA
73C00306	4-1058	NA	NA	NA	NA	NA
73C00307	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00308	No Match	NA	NA	NA	NA	NA
73C00309	5A	5.73E-04	0.02	0.41	0.148	1.309
73C00310	241-AP-6	8.60E-05	0.07	0.40	0.005	1.948
73C00311	5A	5.73E-04	0.02	0.41	0.148	1.309
73C00312	5A	5.73E-04	0.02	0.41	0.148	1.309
73C00313	241-AP-2	5.97E-04	0.10	0.52	0.031	3.087
73C00323	No Match	NA	NA	NA	NA	NA
73C00324	No Match	NA	NA	NA	NA	NA
73C00325	4-1058	NA	0.10	0.57	0.003	1.527
73C00326	4-1058	NA	0.10	0.57	0.003	1.527
73C00327	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00328	No Match	1.20E-04	NA	NA	NA	NA

Table 6-18. Textural Match of Hanford Soil Samples to Nye County Soil Samples and Associated Hydraulic Parameter Values (Continued)

Nye County Soil Sample ID	Hanford Site Soil Sample ID	Saturated Hydraulic Conductivity, K_{sat}, cm/sec	θ_r,	θ_s,	α	n
73C00329	4-1058	NA	0.10	0.57	0.003	1.527
73C00330	D13-08	1.20E-04	0.08	0.45	0.007	1.788
73C00331	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00332	D13-08	1.20E-04	0.08	0.45	0.007	1.788
73C00335	5-0005	6.70E-05	0.04	0.39	0.007	2.243
73C00336	D05-03	5.73E-04	0.02	0.41	0.148	1.309
73C00337	241-AP-6	8.60E-05	0.07	0.40	0.005	1.948
73C00338	4-1058	NA	0.10	0.57	0.003	1.527
73C00339	D09-01	1.20E-04	0.08	0.45	0.007	1.768
73C00340	D14-04	1.20E-04	0.08	0.46	0.007	1.855
73C00341	No Match	NA	NA	NA	NA	NA
73C00342	5-0001	1.40E-04	0.02	0.37	0.006	2.815
73C00343	2-2230	2.30E-04	0.06	0.33	0.007	2.141
73C00344	5A	5.73E-04	0.02	0.41	0.148	1.309
73C00353	No Match	NA	NA	NA	NA	NA
73C00354	No Match	NA	NA	NA	NA	NA
73C00355	No Match	NA	NA	NA	NA	NA
73C00356	No Match	NA	NA	NA	NA	NA
73C00357	No Match	NA	NA	NA	NA	NA
73C00359	No Match	NA	NA	NA	NA	NA
78P03301	D13-08	1.20E-04	0.08	0.45	0.007	1.788
78P03303	D14-04	1.20E-04	0.08	0.46	0.007	1.855
78P03306	5-0005	6.70E-05	0.04	0.39	0.007	2.243
78P03308	D09-01	1.20E-04	0.08	0.45	0.007	1.768
78P03310	D13-08	1.20E-04	0.08	0.45	0.007	1.788
78P03313	D10-04	1.20E-04	0.09	0.45	0.006	1.790
80P00924	241-AP-6	8.60E-05	0.07	0.40	0.005	1.948
87P03200	D09-05	2.90E-04	0.07	0.45	0.009	1.618
87P03201	D14-04	1.20E-04	0.08	0.46	0.007	1.855
87P03202	D14-04	1.20E-04	0.08	0.46	0.007	1.855
87P03203	D11-08	1.20E-04	0.09	0.43	0.006	1.757
87P03204	D09-01	1.20E-04	0.08	0.45	0.007	1.768
87P03205	D10-04	1.20E-04	0.09	0.45	0.006	1.790
92P03331	4-0973	1.27E-04	0.02	0.35	0.017	2.009
92P03332	D14-04	1.20E-04	0.08	0.46	0.007	1.855
92P03335	5-0005	6.70E-05	0.04	0.39	0.007	2.243
92P03339	5-0005	6.70E-05	0.04	0.39	0.007	2.243
92P03340	241-AP-6	8.60E-05	0.07	0.40	0.005	1.948
92P03344	241-AP-6	8.60E-05	0.07	0.40	0.005	1.948
92P03345	5-0005	6.70E-05	0.04	0.39	0.007	2.243
92P03349	4-0644	NA	0.08	0.39	0.007	2.267
92P03350	5-0004	1.65E-04	0.03	0.33	0.012	1.574
92P03351	D10-04	1.20E-04	0.09	0.45	0.006	1.790

Table 6-18. Textural Match of Hanford Soil Samples to Nye County Soil Samples and Associated Hydraulic Parameter Values (Continued)

Nye County Soil Sample ID	Hanford Site Soil Sample ID	Saturated Hydraulic Conductivity, K_{sat}, cm/sec	θ_r,	θ_s,	α	n
92P03352	5-0005	6.70E-05	0.04	0.39	0.007	2.243
92P03353	4-0644	NA	0.08	0.39	0.007	2.267

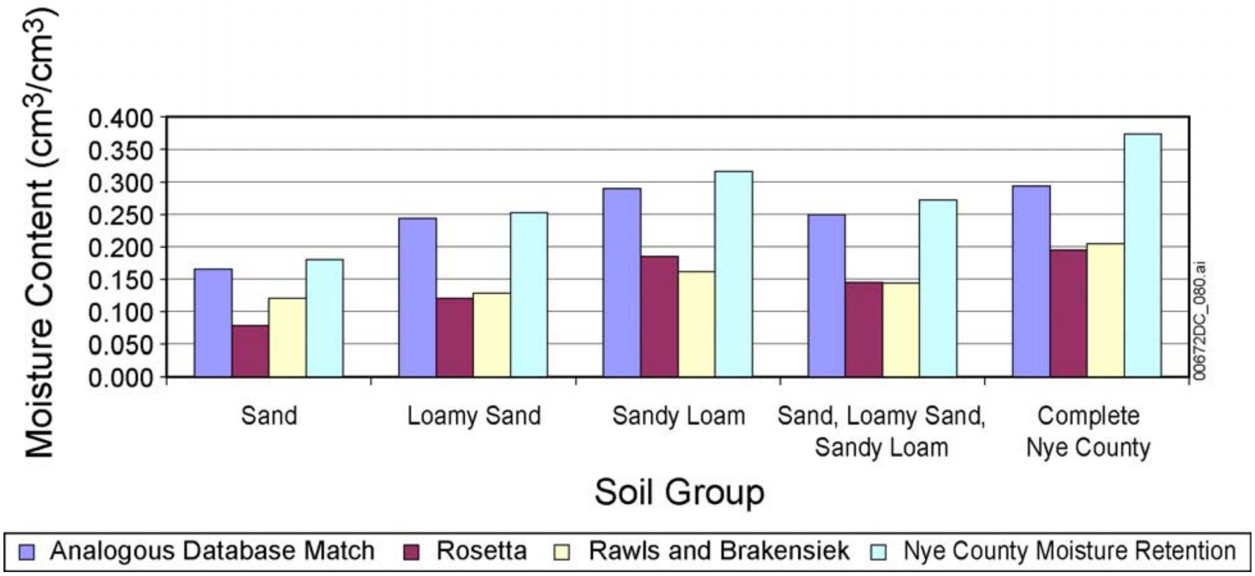
Source: DTN: MO0608SPANYECT.000, *NyeCounty_Hanford_DataMatch_August22_2006.xls*, worksheet 'HanfordMatchtoNyeCo'.

NOTE: Hydraulic parameters are unadjusted for rock fragment content and are from Khaleel and Freeman (1995 [DIRS 175734], Appendices A and B).

ID = identification; NA = not applicable.

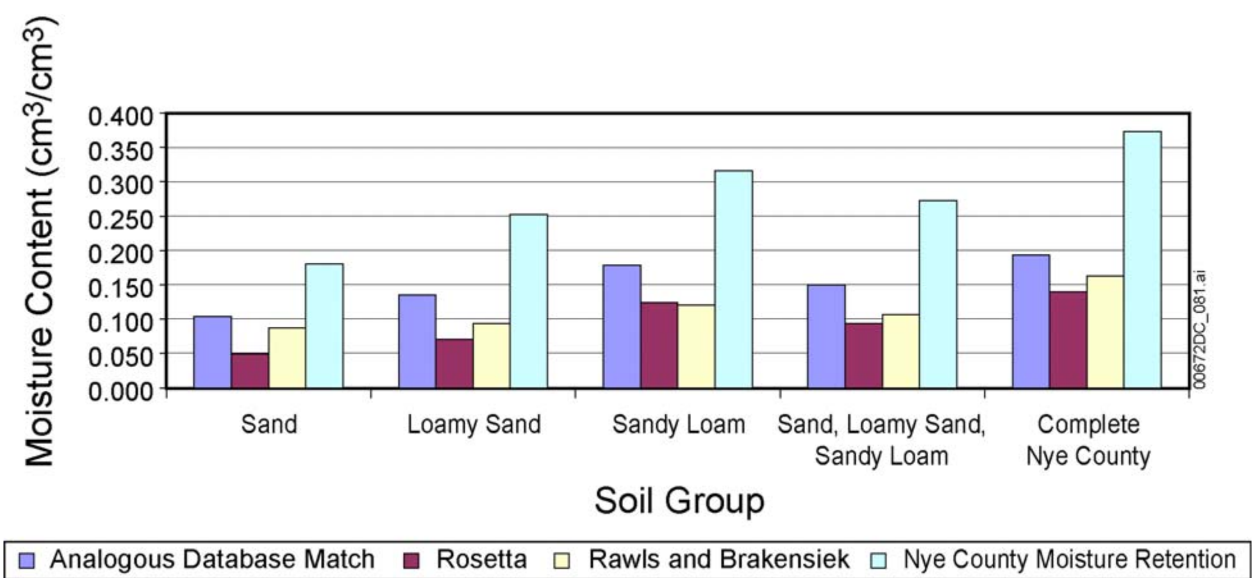
The Nye County-Hanford derived soil hydraulic properties were compared to soil hydraulic properties developed from the two alternative PTFs: the Rawls and Brakensiek method (Rawls and Brakensiek [DIRS 177045] and ROSETTA (Schaap 2001 [DIRS 176006]) in the same manner as the analysis using Yucca Mountain data (Section 6.3) (Appendix C). Additionally, soil moisture retention data at 10 kPa (–0.10 bar) and 33 kPa (–0.33 bar) were available in the Nye County data set, which were compared with the derived moisture contents at –0.10 and –0.33 bar.

The results of the comparison are presented in Figures 6-20 to 6-27, which show the mean values of the Nye County–Hanford derived parameters plotted with the resulting mean values from the two alternative PTF methods (Rawls and Brakensiek 1985 [DIRS 177045]; Schaap 2001 [DIRS 176006]). Summarized in Appendix C are the inputs and approach. The analysis files are available in DTN: MO0608SPANYECT.000. The Nye County moisture data for FC at –0.10 bar show a good match to the analogous database developed moisture data (Figure 6-20). Likewise, the moisture data developed by Rawls and Brakensiek (1985 [DIRS 177045]) and by using ROSETTA at –0.10 bar agree well with each other and are consistently lower than both the Nye County moisture data and the analogous database developed moisture data. At –0.33 bar matric potential, the analogous database developed moisture data more closely matches that developed by Rawls and Brakensiek (1985 [DIRS 177045]) and by using ROSETTA, while the Nye County moisture data are consistently higher than the other three PTFs (Figure 6-12).



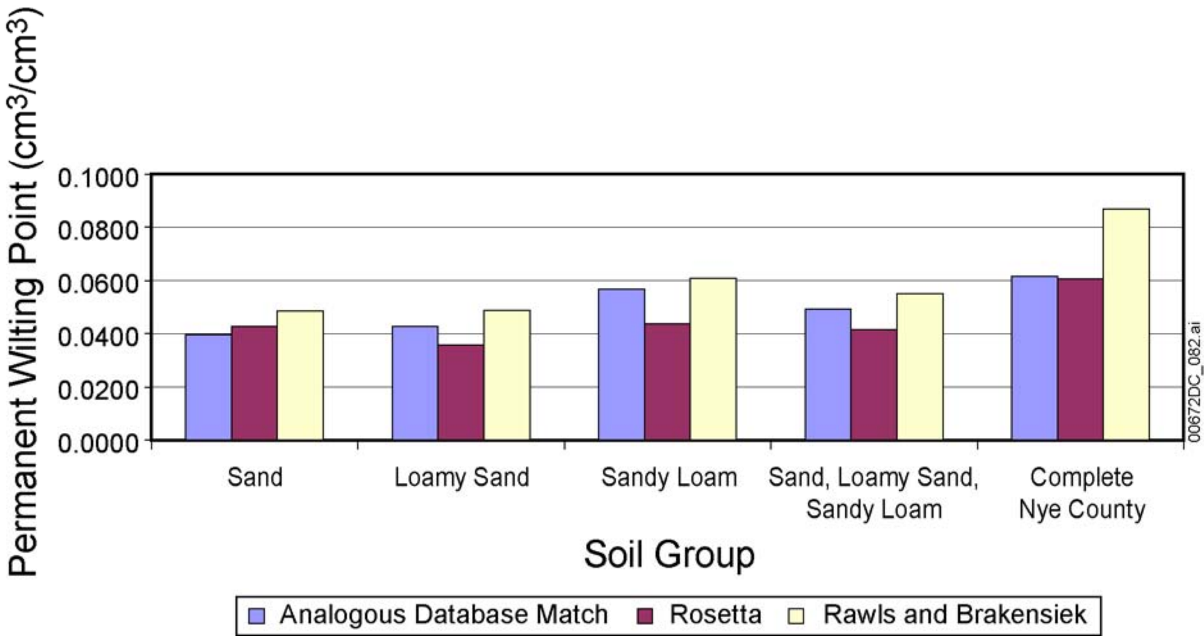
Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-20. Mean Moisture Content Values at –0.10 Bar (–102 cm) for Three Pedotransfer Function Methods Using Nye County Data and Measured Moisture Retention Data from Nye County



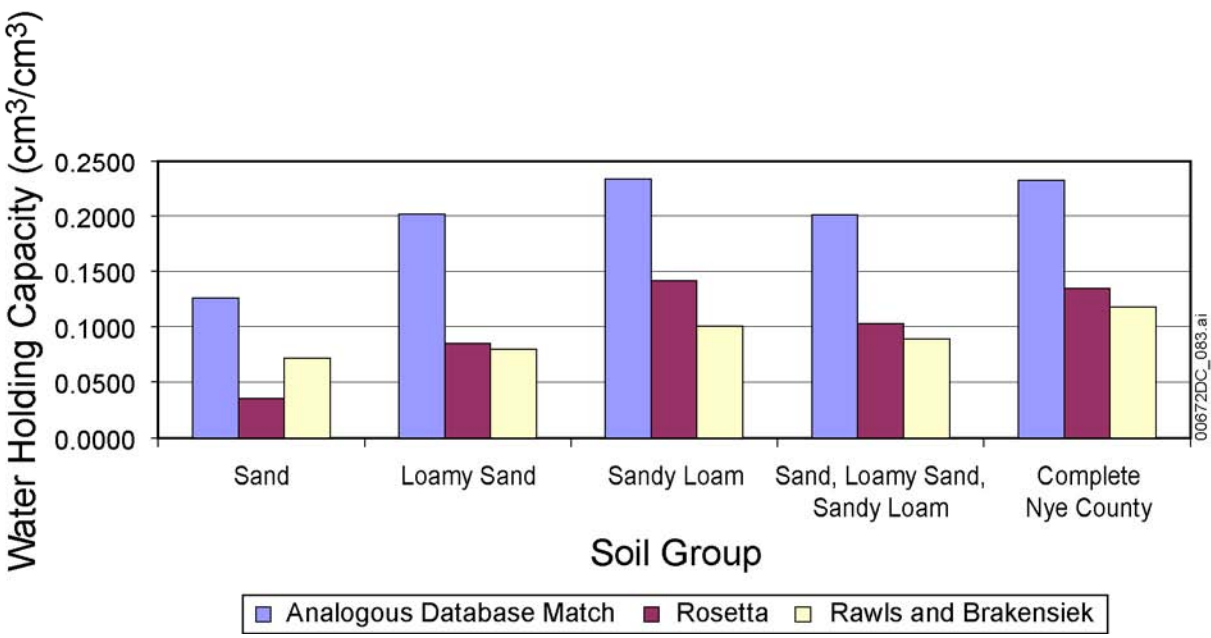
Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-21. Mean Moisture Content Values at –0.33 Bar (–336.6 cm) for Three Pedotransfer Function Methods Using Nye County Data and Measured Moisture Retention Data from Nye County



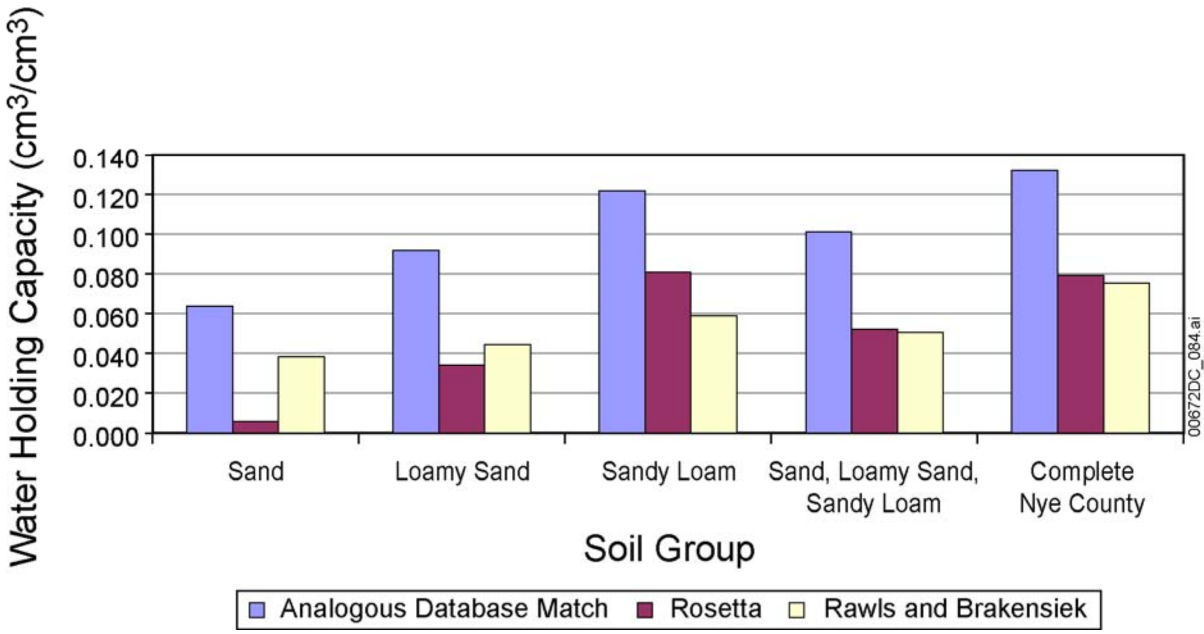
Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_ August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-22. Mean Permanent Wilting Point at −60 Bar for Three Pedotransfer Function Methods Using Nye County Data



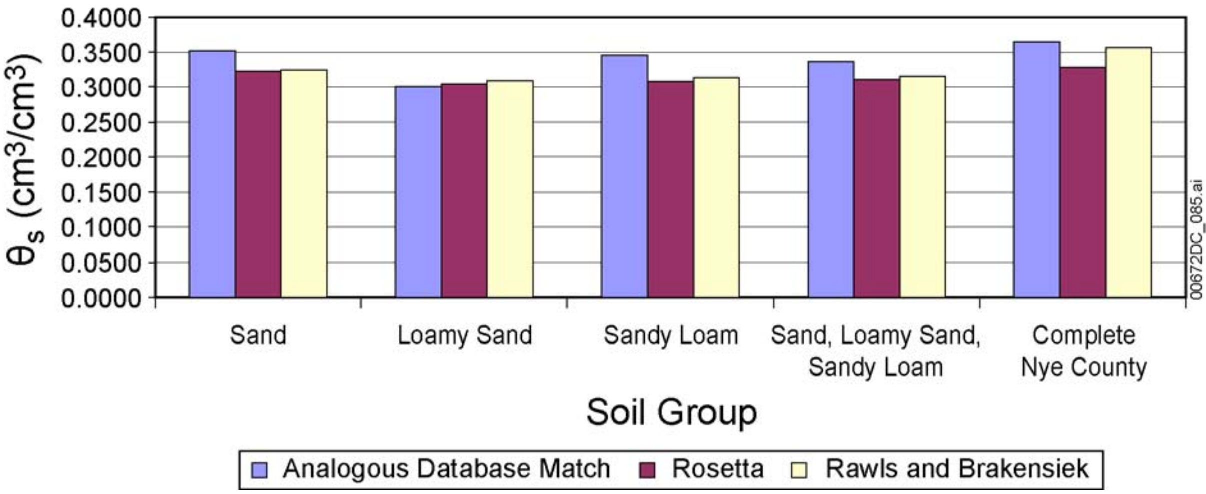
Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_ August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-23. Mean Water Holding Capacity at −0.10 Bar (−102 cm) Field Capacity for Three Pedotransfer Function Methods Using Nye County Data



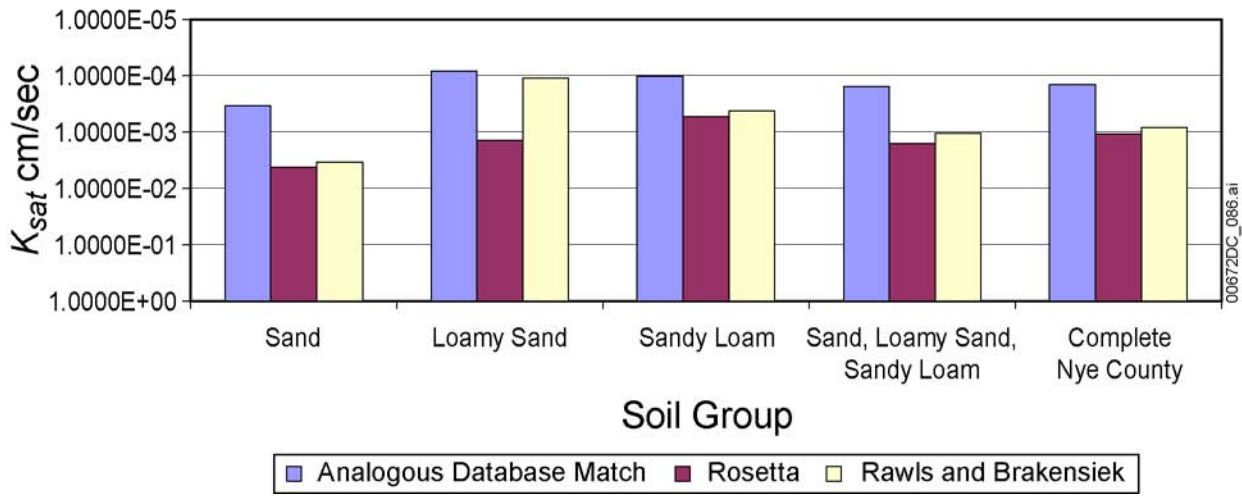
Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_ August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-24. Mean Water Holding Capacity at –0.33 Bar (–336.6 cm) Field Capacity for Three Pedotransfer Function Methods Using Nye County Data



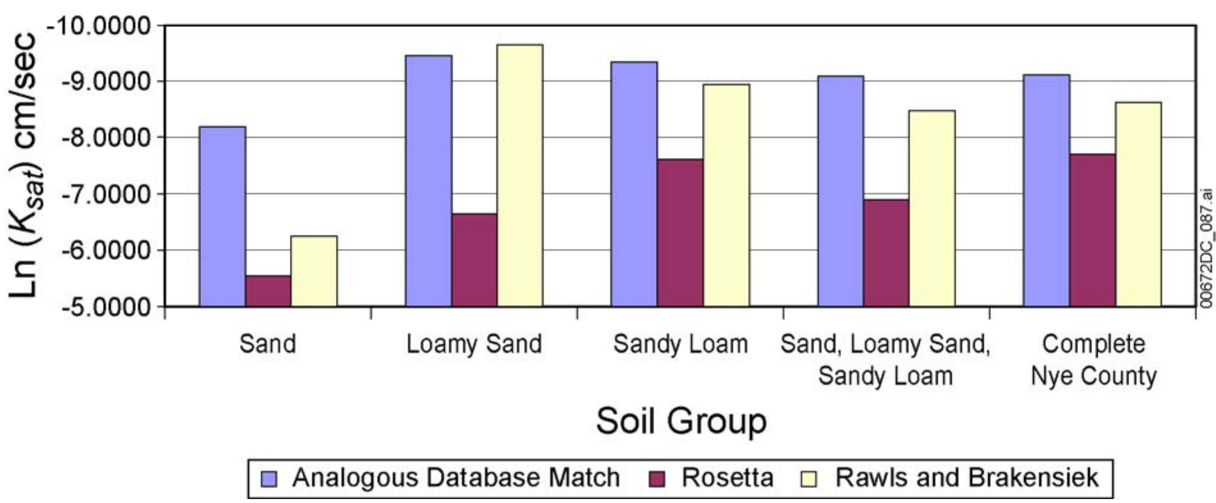
Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_ August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-25. Mean θ_S for Three Pedotransfer Function Methods Using Yucca Mountain Data Using Nye County Data



Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_ August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-26. Mean K_{sat} for Three Pedotransfer Function Methods Using Nye County Data

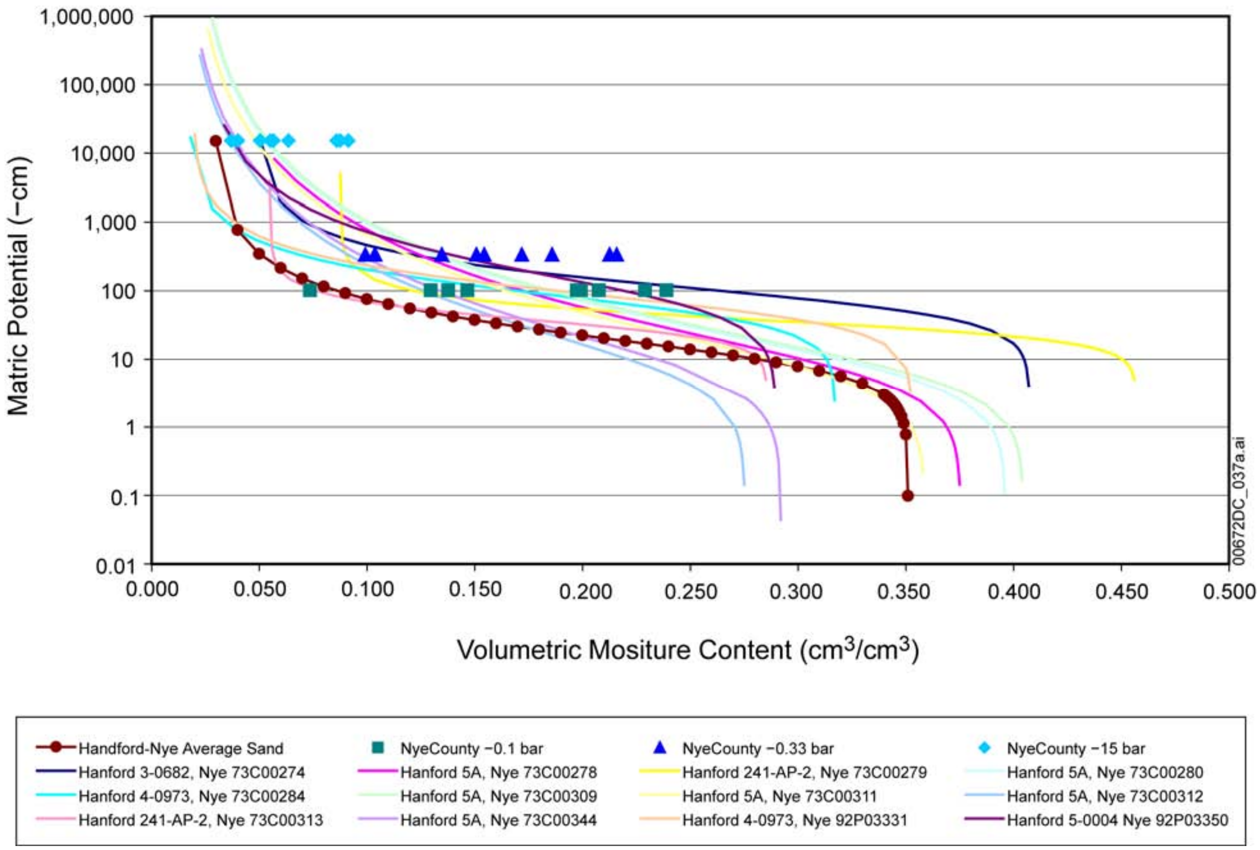


Source: DTN: MO0608SPANYECT.000, *NyeCounty_MethodCorroboration_ August1_2006.xls*, worksheet 'CompareMeans'.

Figure 6-27. Mean Ln (K_{sat}) for Three Pedotransfer Function Methods Using Nye County Data

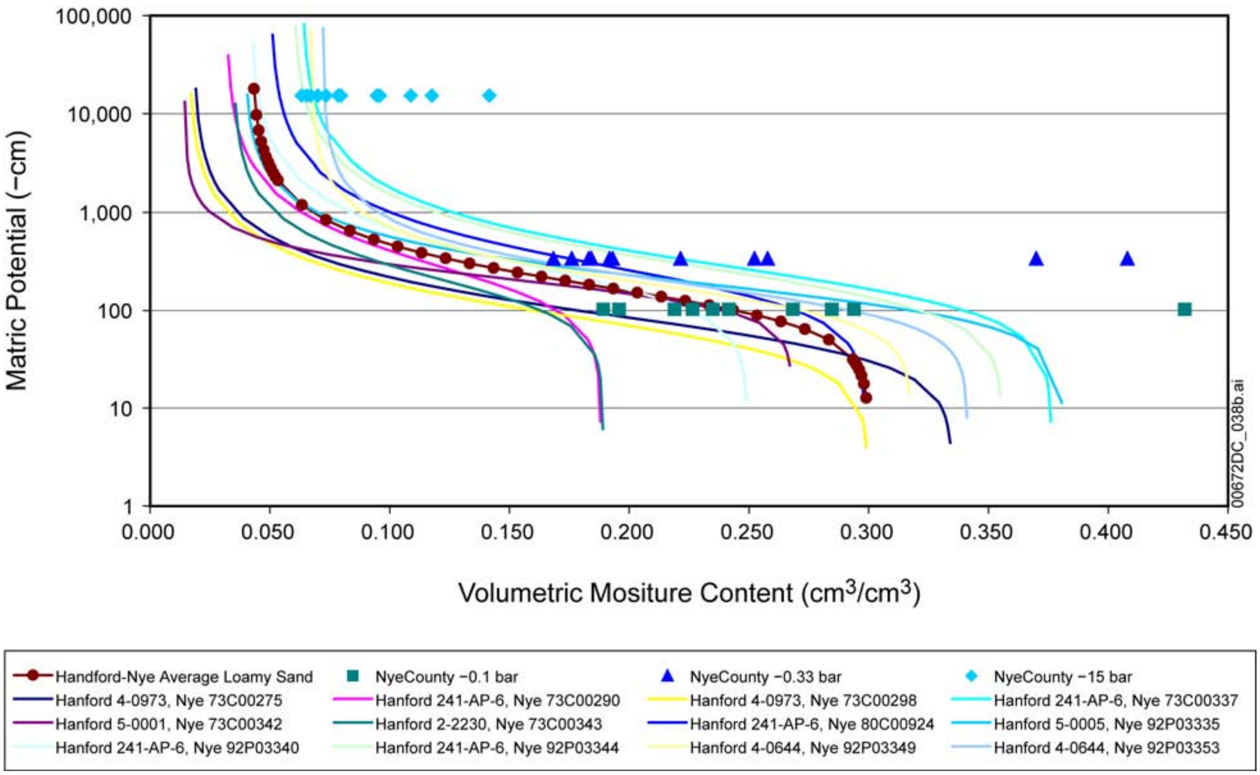
Moisture retention curves plotted, using the Hanford values of θ_r, θ_s, α, and n (Table 6-18), with the van Genuchten equation with the Mualem model (m = 1 – 1/n) (van Genuchten 1980 [DIRS 100610]), are shown in Figures 6-28 to 6-30. The calculations are provided in DTN: MO0608SPANYECT.000. Nye County matric potential versus moisture content data (Table 6-18) are plotted on the curves corresponding to the appropriate Hanford match for comparison. The Nye County used in the plots were organized by layers (samples) representing the USDA soil texture classifications sand, loamy sand, and sandy loam. Figures 6-28 to 6-30 show that the measured Nye County moisture contents are generally located on the "wetter" side of the plot over the Hanford derived data.

There is uncertainty inherent in Nye County data associated with sample collection and laboratory analysis equipment and procedures. This uncertainty combined with the uncertainty associated with the matching approach results in the observed "scatter." Other PTFs, such as those developed by Rawls and Brakensiek (1985 [DIRS 177045]) and by using ROSETTA, have relied solely on soil texture, but have had the benefit of adjusting predictive relationships with site-specific hydraulic data to obtain better agreement between predicted values and site-specific values. These site-specific hydraulic parameter values are not available for Yucca Mountain; the overall match and scatter, however, between Nye County data and Hanford data, are reasonable. Thus, the hydraulic parameter values developed by matching to the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) are appropriate for use to calculate infiltration values at Yucca Mountain.



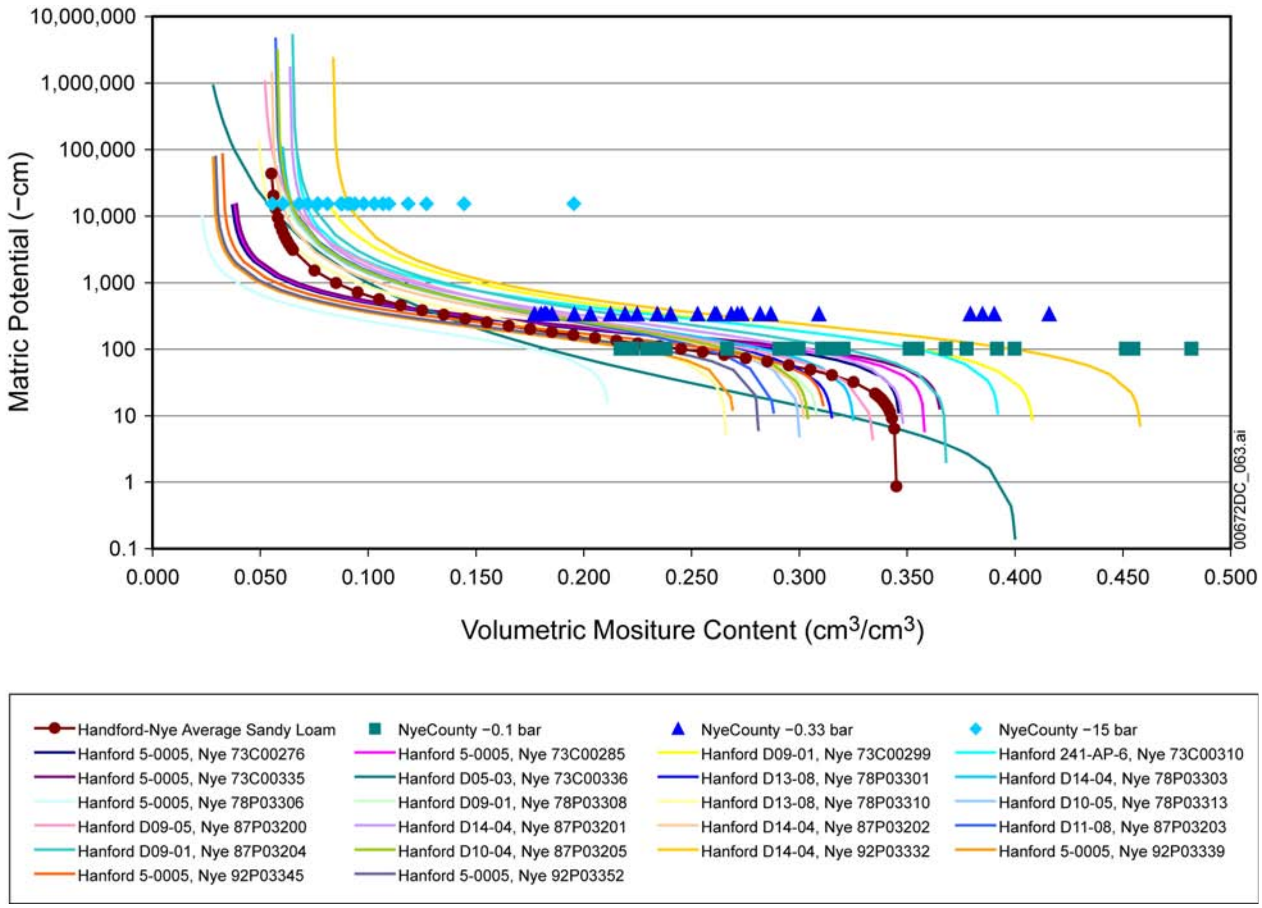
Source: DTN: MO0608SPANYECT.000, *MoistureRetentionCurve_MethodCorroboration_ August22_2006.xls*, worksheet 'Sand MRC'.

Figure 6-28. Moisture Retention Curves for Nye County Developed with Analogous Database Derived Hydraulic Parameters for Nye County Sand



Source: DTN: MO0608SPANYECT.000, *MoistureRetentionCurve_MethodCorroboration_ August22_2006.xls*, worksheet 'Loamy Sand MRC'.

Figure 6-29. Moisture Retention Curves for Nye County Developed with Analogous Database Derived Hydraulic Parameters for Nye County Loamy Sand



Source: DTN: MO0608SPANYECT.000, *MoistureRetentionCurve_MethodCorroboration_ August22_2006.xls*, worksheet 'Sandy Loam MRC'.

Figure 6-30. Moisture Retention Curves for Nye County Developed with Analogous Database Derived Hydraulic Parameters for Nye County Sandy Loam

6.4.7 Comparison of PTF Derived K_{sat} Values with NRCS Nye County and Nevada Test Site Data

Two primary sources of non-YMP K_{sat} data were identified. One set of data are located on the NRCS website (USDA 2006 [DIRS 177088]) in the Soil Data Mart. Soils data can be downloaded from the Soil Data Mart into Microsoft® Access™ and GIS formats through a file transfer protocol site or reports can be formed directly on the website and saved as a portable document format file. Soils data for Nye County are organized into geographical sections, the most relevant to Yucca Mountain soils would be the southwest part, and further separated into functional categories such as physical properties, engineering properties, and taxonomy. Each soil within the database is given a name and number. Nye County soils from the physical properties database have generally the same textures as the Hanford derived Yucca Mountain data of sands, loamy sands, and sandy loams with excessive rock fragments. Saturated hydraulic conductivity range values are provided for depth interval within a given soil name and number.

The K_{sat} values reported in the Nye County Soil Data Mart (USDA 2006 [DIRS 177088]) data are rather coarse. For surface samples (about 0 to −60 cm), K_{sat} values can from vary 1.0E-6 to 1. 41E-2 cm/sec, with most soils having a range between 1.41E-3 to 4.2E-3 cm/sec over a given depth interval. This range is generally about one order of magnitude greater than the mean K_{sat} values presented in Figure 6-7. The mean K_{sat} values shown in Figure 6-15 show a great deal of variability between PTF methods with the Hanford matched data at consistently lower values than the alternate PTF methods. The K_{sat} values for Hanford matched data in 6.15 range from 8.3E-5 t o 3.5E-4 cm/sec, which is within the Nye County range of 1.0E-6 to 1.41E-2 cm/sec, but substantially lower the 1.41E-3 to 4.2E-3 cm/sec range.

The second set of data are in the form of a published paper covering a study of a low-level radioactive waste site at the Nevada Test Site (Istok et al. 1994 [DIRS 176890]). The study site was located within the Radioactive Waste Management Site in northern Frenchman Flat in Area 5 of the Nevada Test Site. The study site is located on an alluvial fan with a slope of approximately 1°, which is representative of the Radioactive Waste Management Site. The K_{sat} data are presented with texture and bulk density data as descriptive statistics representing vertical and horizontal core samples from the course and fine layers removed from a trench (Trench 8) and pit (Pit 3). The fine-grained deposits are described as gravel in a mixture of silty, fine-to-medium sand with weak sedimentary structure. The course-grained deposits consist of sand and gravel layers with numerous small-scale sedimentary structures. Table 6-19 lists the descriptive statistics for the K_{sat} values provided by Istok et al. (1994 [DIRS 176890]). The K_{sat} values listed in Table 6-19 are, in general, one order of magnitude greater than the Hanford derived K_{sat} values presented in Figures 6-7 and 6-15.

Table 6-19. Measured Mean K_{sat} Values from Nevada Test Site Data Low-Level Radioactive Waste Site

Descriptive Statistic	K_{sat} (cm/sec)	Borehole Orientation
Fine Layer: Trench 8		
Mean	8.9E-4	Vertical
Min	1.0E-4	Vertical
Max	4.7E-3	Vertical
Standard Deviation	8.5E-4	Vertical
Mean	6.3E-4	Horizontal
Min	8.8E-5	Horizontal
Max	3.7E-3	Horizontal
Standard Deviation	6.7E-4	Horizontal
Course Layer: Trench 8		
Mean	4.5E-3	Vertical
Min	5.2E-4	Vertical
Max	1.9E-2	Vertical
Standard Deviation	4.2E-3	Vertical
Mean	7.5E-3	Horizontal
Min	1.2E-3	Horizontal
Max	2.2E-2	Horizontal
Standard Deviation	5.2E-3	Horizontal

Table 6-19. Measured Mean K_{sat} Values from Nevada Test Site Data Low-Level Radioactive Waste Site (Continued)

Descriptive Statistic	K_{sat} (cm/sec)	Borehole Orientation
Fine Layer: Pit 3		
Mean	1.9E-3	Vertical
Min	1.9E-4	Vertical
Max	5.6E-3	Vertical
Standard Deviation	1.4E-3	Vertical
Mean	1.9E-3	Horizontal
Min	3.4E-4	Horizontal
Max	8.3E-3	Horizontal
Standard Deviation	1.6E-3	Horizontal
Course Layer: Pit 3		
Mean	3.0E-3	Vertical
Min	1.7E-4	Vertical
Max	3.8E-2	Vertical
Standard Deviation	6.1E-3	Vertical
Mean	3.5E-3	Horizontal
Min	3.2E-4	Horizontal
Max	3.8E-2	Horizontal
Standard Deviation	6.1E-3	Horizontal

Source: Istok et al 1994 [DIRS 176890], Tables 1, 2, 3, and 4.

6.4.8 Goodness of Match

A goodness-of-match calculation between the YMP soil samples and the Hanford soil samples was performed by first determining the difference between sand, silt, and clay fractions, then calculating the ED, which is a three-dimensional representation of the distance between the three parameters of sand, silt, and clay. The EDs for the YMP and Hanford match samples were calculated (Section 6.3.2) and the resulting values provide some measure of how well the textural data match. Appendix A lists the EDs for the matched samples with a value of zero indicating an exact match.

The quality of the match between Yucca Mountain soil samples and analogous database soil samples is quantifiable and matches were selected that had the smaller ED. Yucca Mountain samples with large clay content (20% or greater) could not be matched to data in the available analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B).

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7. CONCLUSIONS

This analysis documents the verification of soil unit definition and areal distribution, and development of soil-specific hydraulic parameters for Yucca Mountain. The assessment of soils and the development of associated hydraulic properties address the criteria identified in Section 4.2. Soil unit definitions, distributions, and associated hydraulic properties presented herein are sufficient to provide input to a replacement infiltration model. The soil hydraulic parameter data generated in this analysis are intended for use only in a replacement infiltration model (Section 1). No other subsequent use restrictions have been identified.

7.1 SUMMARY OF ANALYSIS

The following sections summarize the verification of soil unit definitions and the results of hydraulic parameters that were developed, along with associated uncertainties.

7.1.1 Taxonomic Groupings of Soil Units

The purpose of the verification discussed in Section 6.2 is to review the grouping of surficial mapping units into soil units in DTN: GS960408312212.005 [DIRS 146299] for use in the simulation of net infiltration, to assess the appropriateness of the grouping, and to provide an explanation of the grouping or an alternative approach for developing model inputs. Criteria used to determine the appropriateness of the soil unit groupings in DTN: GS960408312212.005 [DIRS 146299] include the amount of clay accumulation in the deposits, the extent of pedogenic calcium carbonate accumulated in the deposits, and variation in the particle-size distribution. Soil unit groupings can be verified with these criteria. The soil units defined in the DTN are appropriate for use to develop hydraulic parameters for input to a replacement infiltration model. Table 6-2 lists the soil units. Soil Units 1 to 7 and 9 have been used to derive hydraulic properties, while Soil Unit 8, representing bedrock, and Soil Unit 10, representing disturbed soils such as roads and drilling pads, have not been used. The hydraulic properties of bedrock (Soil Unit 8) are developed in *Data Analysis for Infiltration Modeling: Bedrock Saturated Hydraulic Conductivity Calculation* (BSC 2006 [DIRS 176355]).

7.1.2 Soil Hydraulic Parameters

The following parameter values were developed as part of the input to a replacement infiltration model:

- Saturated hydraulic conductivity, K_{sat}
- FC, which is defined as the moisture content at –0.33 bar and –0.10 bar
- PWP, which is defined as the moisture content at –60 bar
- Saturated moisture content, θ_s
- WHC, which is defined as the difference between the FC and PWP (for alternate soil groups 1 and 2 only).

These parameters were developed by matching textural data from Yucca Mountain soil samples collected at various locations within the model grid to textural data from the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B). Hydraulic parameter values associated with the sample matched to the analogous site database were then assigned to the Yucca Mountain sample. The next step was to develop the representative distribution of hydraulic parameter for each soil unit. For the base case soil grouping, a representative value for each parameter at each sample location is determined. For situations where only one soil sample was identified at a discrete coordinate, the corresponding set of hydraulic parameter values was assigned without any further adjustment and provided in output DTN: MO0605SPASOILS.005, worksheet 'SoilUnitXStatistics', where X represents a soil unit number. Where multiple YMP soil samples were identified at the same coordinate, the geometric mean of the K_{sat} values and the arithmetic mean of α, n, FC moisture content, PWP moisture content, θ_r, and θ_s were determined and provided in output DTN: MO0605SPASOILS.005, worksheet 'SoilUnitXStatistics'.

Thus, for the base case soil grouping, one set of representative hydraulic parameter values is developed for each discrete coordinate. The geometric mean of the K_{sat} values and the arithmetic mean of FC moisture content, PWP moisture content, and θ_s were determined for representative values at each sample location for each soil unit. For alternate soil groups 1 and 2, there was no attempt to develop representative samples at each sample location. The geometric mean of the K_{sat} values and the arithmetic mean of FC moisture content, PWP moisture content, WHC, and θ_s, were determined for each soil unit as a group. The geometric mean results in an intermediate K_{sat} value between the harmonic and arithmetic mean (Section 6.3.4) and provides the best representation for the infiltration model area given the potential for soil layering, small and large-scale heterogeneities, occurrence of sloping surfaces, and soil textures that are encountered in the infiltration model area (Domenico and Schwartz 1990 [DIRS 100569], p. 67). The harmonic mean has application in layered systems where flow is vertical and could be appropriate for a lumped-parameter mass-balance bucket model, such as the infiltration model for Yucca Mountain (BSC 2006 [DIRS 177492]). The use of the harmonic mean, however, would result in lower average K_{sat} values which could underestimate infiltration, compared to those calculated using the recommended geometric mean.

A statistical analysis was performed on the resulting hydraulic properties. Descriptive statistics and estimated correlations for K_{sat}, FC moisture content, PWP moisture content, and θ_s are provided in Tables 6-7 and 6-9 for the base case soil grouping, respectively. Descriptive statistics were calculated using the standard Excel® DESCRIPTIVE STATISTICS function and are provided in output DTN: MO0605SPASOILS.005, worksheet 'SoilUnitXDescripStatistics', where X represents a soil unit number. For alternate soil groups 1 and 2, descriptive statistics for K_{sat}, FC, PWP, and WHC were developed and provided in output DTN: MO0605SEPALTRN.000 and summarized in Tables 6-11 and 6-12, respectively. Distribution type evaluation for alternate soil groups 1 and 2 is provided in Appendix D.

7.2 DATA TRACKING NUMBERS FOR DATA GENERATED IN THIS ANALYSIS

Table 7-1 summarizes the data generated in this analysis for use in a replacement infiltration model.

Table 7-1. Output Derived for Use in a Replacement Yucca Mountain Project Infiltration Model

Data Tracking Number	Title	Description	Location in Text
MO0605SEPALTRN.000	Alternative Soil Units, Hydraulic Parameters, and Associated Statistics for Infiltration Modeling at Yucca Mountain, NV	Provides the development of two alternative soil unit groupings, soil hydraulic parameters, and statistics	Tables 6-11 and 6-12
MO0605SEPDEVSH.002	Development of Soil Hydraulic Parameters for Infiltration Modeling at Yucca Mountain, NV	Provides the overall development used to derive the hydraulic parameters and the statistical evaluation for Yucca Mountain Soil Units 1 to 7, and 9. Development of soil hydraulic parameters was performed in Excel® worksheets and is organized Into eight separate workbooks - one for each soil unit. These data supersede data previously identified by DTN: MO0604SEPDEVSH.001.	Sections 6.3.4 and 6.3.4.1; Table 6-7
MO0605SEPFCSIM.000	Field Capacity of Soils at −1/10 Bar and Associated Statistics for Infiltration Modeling at Yucca Mountain, NV	Provides the development used to derive the field capacity at −1/10 bar and the statistical evaluation for Yucca Mountain Soil Units 1 to 5, along with 7 and 9. Development of the field capacity soil parameter was performed in Excel® worksheets and is organized into 21 separate workbooks - three for each of the seven soil units.	Table 6-7
MO0605SPASOILS.005	Soil Hydraulic Parameters and Associated Statistics for Infiltration Modeling at Yucca Mountain, NV	Provides soil units and associated hydraulic parameter values for the Yucca Mountain area infiltration model. This file supersedes data identified in DTN: MO0604SPASOILS.004.	Sections 6.3.4 and 6.3.4.1; Tables 6-7 to 6-9

7.3 UNCERTAINTIES AND LIMITATIONS

The following discussion summarizes uncertainties identified in Section 6.4 and an uncertainty associated with the definition of FC described in Section 5.3.

The effect of pedogenic product development on hydraulic parameters of soil units would slow the movement of infiltrating water through the soil. Therefore, the development of hydraulic properties, based on only particle size distributions, overestimate the rate of infiltration in soil units where these products are present. The sample collection methods and laboratory analysis procedures used for Yucca Mountain data and data in the analogous site database of Hanford soil hydraulic parameters were found to be well documented and reasonable for their intended use (Section 6.4). The Yucca Mountain sample locations are clustered in the center of the model area, rather than evenly or randomly distributed over the entire model area (Section 6.4.2). The lack of sample locations at the edges of the model area results in greater uncertainty with increasing distance from the clusters of samples.

Local available data were found to be lacking required qualification or missing important hydraulic parameter or moisture-retention curve-related data (Section 6.4.3). Nye County data (USDA 2006 [DIRS 176439]) were found to be useful in demonstrating reasonableness of the approach, but were not sufficient to use as an analogue for Yucca Mountain hydraulic parameters. The results of this analysis suggest that the matching approach using the analogous site database (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) would be less uncertain if additional data, such as bulk density, were available for Yucca Mountain and Hanford (Section 6.4.4). The matching approach (Section 6.4.5) was found to be reasonable, based on an evaluation of matching Nye County data (USDA 2006 [DIRS 176439]) to the analogous site database of Hanford soil hydraulic parameters (Khaleel and Freeman 1995 [DIRS 175734], Appendices A and B) and to two alternative PTFs.

Method corroboration was performed by (1) comparing the analogous site matching approach to two other PTFs (Rawls and Brakensiek 1985 [DIRS 177045]) and that of ROSETTA, (Schaap et al. 2001 [DIRS 176006], pp. 163 to 176) and (2) comparing the analogous site matching approach to Nye County data (Section 6.4.5 and 6.4.6). The FC moisture contents derived from the analogous site database method are slightly larger than the other two PTFs. This increase in moisture content is also manifested in the WHC based on –0.10 and –0.33 bar matric potential. The greater WHC calculated using the analogous site database compared to WHC calculated by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and by using ROSETTA is unexpected.

The development of the regression coefficients by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) are likely, based on agricultural soils and soils from temperate to subtropical climates, including soils from the USDA UNSODA (unsaturated soil hydraulic properties) database, like the database used in ROSETTA. Soils from temperate and subtropical climates and agricultural soils generally have larger holding capacities compared to desert soils.

The K_{sat} values among the three methods agree well with one another. Uncertainty with respect to the moisture contents and holding capacities may be increased based on the results of the analysis, and uncertainty in K_{sat} may be reduced.

When the analogous site matching approach is compared to Nye County moisture data, a similar trend is observed. Nye County moisture data for FC at –0.10 bar matric potential show a good match to the analogous database-developed moisture data (Section 6.4.6). Likewise, moisture data developed by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and by using ROSETTA at –0.10 bar matric potential agree well with each other and are consistently lower than both the Nye County moisture data and the analogous database-developed moisture data. At –0.33 bar matric potential, the analogous database-developed moisture data more closely matches that developed by Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and by using ROSETTA, while the Nye County moisture data are consistently higher than the other three PTFs (Section 6.4.6). The higher moisture contents observed in the Nye County data may be associated with the buildup of pedogenic carbonate in the soil, which can increase the WHC (Section 6.2.3.1). Neither the Nye County data nor the Yucca Mountain data are sufficient to quantify potential bias that could result from not considering the pedogenic carbonate. The suggested approach to sampling WHC (Section 6.3.4.2) for infiltration modeling should capture the relevant uncertainty, however the effect of this potential bias should be evaluated.

An uncertainty involved in the evaluation of net infiltration deals with the definition of FC. Field capacity has been defined as the soil moisture content at which internal drainage ceases, based on observations that the rate of flow and water-content changes decrease with time after a precipitation or irrigation event (Hillel 1980 [DIRS 100583], p. 67). Although matric potentials of −0.33 bar or −0.10 bar have been used to correlate measurements of soil moisture storage in the field (Section 5.3), these criteria do not apply universally to all soils and all conditions (Hillel 1980 [DIRS 100583], p. 70). Alternative approaches have been suggested, such as using an unsaturated hydraulic conductivity equal to 10^{-8} cm/sec where it is assumed that the drainage rate is negligible as discussed in NUREG/CR-6565 (Meyer et al. 1997 [DIRS 176004], p. 6), but there remains the difficulty of determining the definition of negligible flux. For the development of inputs to an infiltration model, the FC values, based on both matric potentials of –0.33 bar and –0.10 bar, are developed to capture the uncertainty inherent with the FC concept.

7.4 YUCCA MOUNTAIN REVIEW PLAN ACCEPTANCE CRITERIA

Section 4.2 presents NUREG-1804 (NRC 2003 [DIRS 163274]) acceptance criteria that are addressed by the soil hydraulic parameter analysis. Table 7-2 identifies where the acceptance criteria have been addressed.

Table 7-2. Acceptance Criteria

Acceptance Criteria	Subcriteria	Sections Where Addressed
Acceptance Criteria 1: System description and model integration are adequate (NRC 2003 [DIRS 163274], Section 2.2.1.3.5.3)	The aspects of geology, hydrology, geochemistry, physical phenomena, and couplings, that may affect climate and net infiltration, are adequately considered. Conditions and assumptions in the abstraction of climate and net infiltration are readily identified and consistent with the body of data presented in the description.	Analysis considers the aspects of soil and how those aspects affect net infiltration. Assumptions and conditions are described in Sections 4 through 6.
Acceptance Criterion 2: Data are sufficient for model justification (NRC 2003 [DIRS 163274], Section 2.2.1.3.5.3)	Climatological and hydrological values used in the license application (e.g., time of onset of climate change, mean annual temperature, mean annual precipitation, mean annual net infiltration, etc.) are adequately justified. Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided.	Sections 4.1 and 6.2 justify and describe the definition of soil units for modeling of net infiltration. Sections 4.1 and 6.3 justify and describe the approach for developing the soil hydraulic values.
	The effects of fracture properties, fracture distributions, matrix properties, heterogeneities, time-varying boundary conditions, evapotranspiration, depth of soil cover, and surface-water runoff and run-on are considered, such that net infiltration is not underestimated.	Section 6.3 discusses the effect of soil matrix properties on the hydraulic properties derived for the soil units.
	Sensitivity or uncertainty analyses are performed to assess data sufficiency and determine the possible need for additional data.	Sensitivity or uncertainty analyses are presented in Section 6.4.

Table 7-2. Acceptance Criteria (Continued)

Acceptance Criteria	Subcriteria	Sections Where Addressed
Acceptance Criterion 3: Data uncertainty is characterized and propagated through the model abstraction (NRC 2003 [DIRS 163274], Section 2.2.1.3.5.3)	Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in an under-representation of the risk estimate.	Uncertainty in the definition of soil units and in the developed soil hydraulic parameter values are discussed in Section 6.4.
	The technical bases for the parameter values used in this abstraction are provided.	Sections 4.1, 6.2, and 6.3 provide the technical bases for the parameters developed in the analysis.
	Possible statistical correlations are established between parameters in this abstraction. An adequate technical basis or bounding argument is provided for neglected correlations.	Statistical correlations are discussed in Section 6.4.

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MO0605SEPDEVSH.002. Development of Soil Hydraulic Parameters for Infiltration Modeling at Yucca Mountain, NV. Submittal date: 5/2/06.

MO0605SEPFCSIM.000. Field Capacity of Soils at −1/10 Bar and Associated Statistics for Infiltration Modeling at Yucca Mountain, NV. Submittal date: 5/26/06.

MO0605SPASOILS.005. Soil Hydraulic Parameters And Associated Statistics For Infiltration Modeling At Yucca Mountain, NV. Submittal date: 5/2/2006.

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APPENDIX A

EUCLIDEAN DISTANCES FOR MATCHES BETWEEN HANFORD AND YUCCA MOUNTAIN SOIL SAMPLES BASED ON FRACTION OF SAND, SILT, AND CLAY

GOODNESS-OF-MATCH

A goodness-of-match calculation between the YMP and Hanford soil samples was performed by first determining the difference between sand, silt, and clay fractions, then calculating the ED, which is a three-dimensional representation of the distance between the three parameters of sand, silt, and clay. The EDs for the YMP and Hanford match samples were calculated (Section 6.3.2) and the resulting values provide some measure of how well the textural data match. A value of zero indicates an exact match. The expression used to calculated ED between sand, silt, and clay for a pair of Yucca Mountain and Hanford soil samples is:

$$\mathrm{ED\ (3D)} = [(\mathrm{Sand}_{ymp} - \mathrm{Sand}_{Hanford})^2 + (\mathrm{Silt}_{ymp} - \mathrm{Silt}_{Hanford})^2 + (\mathrm{Clay}_{ymp} - \mathrm{Clay}_{Hanford})^2]^{1/2}$$

The calculated EDs for the sample matches are provided in Tables A-1 through A-7.

Table A-1. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 1

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D04-10	Sandy Loam	U1DR1	0.1273	NA
D11-08	Sandy Loam	U1DR2	0.1556	NA
D12-14	Sandy Loam	U1DR3	0.0849	NA
3-0651	Loamy Sand	U1DR4	0.0980	NA
NO MATCH	NA	U1DR5	NO MATCH	Justification for no match: equally high values of silt and clay, no corresponding Hanford match.
D04-04	Sandy Loam	U1DR6	0.0849	NA
3-0649	Loam	SF29-1	0.0616	NA
3-0649	Loam	SF29-2	0.0748	NA
D02-10	Sandy Loam	SF29-3	0.0000	NA
D11-08	Sandy Loam	MWV9-1	0.1700	NA
D12-14	Sandy Loam	MWV9-2	0.0990	NA
D08-15	Sandy Loam	MWV9-3	0.1208	NA
3-0689	Sandy Loam	MWV9-4	0.0141	NA
D09-01	Sandy Loam	MWV9-5	0.0927	NA
D04-10	Sandy Loam	MWV11-1	0.0173	NA
D08-15	Sandy Loam	MWV11-2	0.0141	NA
D13-08	Sandy Loam	MWV11-3	0.0000	NA
D02-16	Sandy Loam	MWV11-4	0.0173	NA
D02-10	Sandy Loam	MWV11-5	0.0173	NA
5-0005	Sandy Loam	MWV12-1	0.0374	NA
3-0653	Sandy Loam	MWV12-2	0.0648	NA
3-0690	Sandy Loam	MWV12-3	0.0374	NA
3-0653	Sandy Loam	MWV12-4	0.0787	NA
3-0653	Sandy Loam	MWV12-5	0.0927	NA

Table A-1. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 1 (Continued)

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
3-0649	Loam	MWVP23-Avk	0.0490	NA
5-0005	Sandy Loam	MWVP23-2Btkq	0.0283	NA
4-0973	Loamy Sand	MWVP23-2Btkqm	0.0245	NA
25A	Loamy Sand	MWVP23-2Kqm	0.0100	NA
25A	Loamy Sand	MWVP23-2Kq	0.0100	NA
5-0004	Sand	MWVP23-2Bkq	0.0283	NA
1-1417	Sand	MWVP23-2Ck	0.0141	NA
3-0649	Loam	MWVP25-Avk	0.0436	NA
D13-08	Sandy Loam	MWVP25-2Btkj	0.0000	NA
5-0005	Sandy Loam	MWVP25-3Bkq	0.0283	NA
241-AP-6	Loamy Sand	MWVP25-3Kqym	0.0469	NA
5-0005	Sandy Loam	MWVP25-2Kqy	0.0245	NA
19A	Loamy Sand	MWVP25-3Bkq1	0.0469	NA
2-2230	Loamy Sand	MWVP25-3Bkq2	0.0548	NA
0-082	Loamy Sand	MWVP25-4Bkq	0.0245	NA
5A	Sand	MWVP25-4Ckq1	0.0173	NA
5A	Sand	MWVP25-4Ckq2	0.0245	NA
D09-01	Sandy Loam	MWVP13-Avk	0.0224	NA
3-0649	Loam	MWVP13-Btkq	0.0361	NA
241-AP-6	Loamy Sand	MWVP13-2Kqb	0.0173	NA
19A	Loamy Sand	MWVP13-Bkqb	0.0245	NA
3-0682	Sand	MWVP13-2Bkq2b	0.0141	NA
1-1417	Sand	MWVP13-2BCkqb	0.0173	NA
4-0644	Loamy Sand	MWVP13-3Bkqb2	0.0141	NA
5A	Sand	MWVP13-3Bkq2b2	0.0300	NA
3-0690	Sandy Loam	MWVP13-3Bqb2	0.0566	NA
D13-08	Sandy Loam	CF1-SPI-Avk	0.0100	NA
3-0649	Loam	CF1-SPI-Bk	0.0141	NA
3-0651	Loamy Sand	CF1-SPI-2Kqmb1	0.0866	NA
3-0651	Loamy Sand	CF1-SPI-3Kqmb1	0.0990	NA
2-2230	Loamy Sand	CF1-SPI-4Bkb1	0.0640	NA
0-082	Loamy Sand	CF1-SPI-5Bkb1	0.0346	NA
241-AP-6	Loamy Sand	CF1-SPI-6Bkb2	0.0224	NA
241-AP-6	Loamy Sand	CF1-SPII-Av	0.0100	NA
D05-03	Sandy Loam	CF1-SPII-Bk1	0.0436	NA
D05-03	Sandy Loam	CF1-SPII-Bk2	0.0141	NA
19A	Loamy Sand	CF1-SPII-2Kqmb1	0.0200	NA
25A	Loamy Sand	CF1-SPII-3Bkqmb2	0.0141	NA
4-0855	Sand	CF1-SPII-4Bkb2	0.0283	NA
4-0855	Sand	CF1-SPII-5Bkb2	0.0141	NA
D02-10	Sandy Loam	MWVP26-Avkq	0.0990	NA
D04-04	Sandy Loam	MWVP26-Bw	0.0748	NA

Table A-1. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 1 (Continued)

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D04-04	Sandy Loam	MWVP26-2Btjq	0.0510	NA
NO MATCH	NA	MWVP26-2Bwkfqmb	NO MATCH	Justification for no match: very low silt value, no corresponding Hanford match.
D05-03	Sandy Loam	MWVP26-2Btkqb	0.0300	NA
D02-16	Sandy Loam	MWVP26-2Btqb	0.0995	NA
241-AP-6	Loamy Sand	MWVP26-3Kqymb	0.0224	NA
4-0855	Sand	MWVP26-3Bkqvb	0.0283	NA
4-0855	Sand	MWVP26-3BCkqb	0.0245	NA
0-101	Sand	MWVP26-3Ckqb	0.0707	NA
D14-04	Sandy Loam	MWVP28-Avk	0.0787	NA
D04-10	Sandy Loam	MWVP28-BAtq	0.0361	NA
NO MATCH	NA	MWVP28-Btq	NO MATCH	Justification for no match: extremely low sand value and high silt value, no corresponding Hanford match.
4-1058	Loam	MWVP28-Btkq	0.0927	NA
4-1058	Loam	MWVP28-2Btkq2	0.0787	NA
5-0005	Sandy Loam	MWVP28-3Btkqb	0.0141	NA
5-0005	Sandy Loam	MWVP28-3Bkqmb	0.0616	NA
4-0973	Loamy Sand	MWVP28-3Bkqb	0.0300	NA
4-0855	Sand	MWVP28-3BCkqb	0.0424	NA
3-0682	Sand	MWVP28-3Ckqb	0.0141	NA
19A	Loamy Sand	MWVP28-4Bqb2	0.0332	NA
19A	Loamy Sand	MWVP28-4Bkqb2	0.0447	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit1_HydProps_5-1-06.xls*, worksheet 'MatchUncertainty'.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

Table A-2. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 2

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
3-0649	Loam	SF28-1	0.0707	NA
3-0649	Loam	SF28-2	0.0374	NA
D05-03	Sandy Loam	SF28-3	0.0374	NA
D04-04	Sandy Loam	SF31-1	0.0000	NA
D05-03	Sandy Loam	SF31-2	0.0283	NA
D02-16	Sandy Loam	SF31-3	0.0000	NA
3-0689	Sandy Loam	SF31-4	0.0141	NA

Table A-2. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 2 (Continued)

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D04-04	Sandy Loam	SF31-5	0.0374	NA
D02-16	Sandy Loam	SF31-6	0.0000	NA
3-0647	Loamy Sand	U5DR6	0.0374	NA
4-0644	Loamy Sand	U5DR7	0.0000	NA
4-0973	Loamy Sand	SF30-6	0.0141	NA
NO MATCH	NA	U3DR4	NO MATCH	Justification for no match: sand, silt and clay fractions not available in source data.
NO MATCH	NA	U3DR5	NO MATCH	Justification for no match: sand, silt and clay fractions not available in source data.
NO MATCH	NA	U3DR6	NO MATCH	Justification for no match: sand, silt and clay fractions not available in source data.
3-0688	Sandy Loam	MWV10-1	0.0283	NA
241-AP-5	Sandy Loam	MWV10-2	0.0490	NA
241-AP-5	Sandy Loam	MWV10-3	0.0424	NA
241-AP-5	Sandy Loam	MWV10-4	0.0361	NA
D11-06	Sandy Loam	MWV10-5	0.0424	NA
5-0004	Sand	MWV3-1	0.0141	NA
h0-101	Sand	MWV3-2	0.0141	NA
h0-082	Loamy Sand	MWV3-3	0.0173	NA
4-0855	Sand	MWV3-4	0.0141	NA
4-0855	Sand	MWV3-5	0.0283	NA
h0-085	Loamy Sand	MWV4-1	0.0300	NA
h0-073	Loamy Sand	MWV4-2	0.0458	NA
241-AP-6	Loamy Sand	MWV4-3	0.0245	NA
h0-073	Loamy Sand	MWV4-4	0.0141	NA
3-0651	Loamy Sand	MWV4-5	0.1122	NA
NO MATCH	NA	MWVP15-Avk	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
NO MATCH	NA	MWVP15-BAtvk	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.

Table A-2. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 2 (Continued)

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D09-01	Sandy Loam	MWVP15-Btk	0.0990	NA
h0-073	Loamy Sand	MWVP15-2Btkq	0.0245	NA
D05-03	Sandy Loam	MWVP15-3Btkqb	0.0787	NA
3-0651	Loamy Sand	MWVP15-4Bkqb2	0.0374	NA
NO MATCH	NA	MWVP15-4Bkq2b2	NO MATCH	Justification for no match: zero silt value, no corresponding Hanford match.
h0-073	Loamy Sand	MWVP15-4Bkq3b2	0.0283	NA
4-0855	Sand	MWVP15-4BCkqb2	0.0283	NA
4-0855	Sand	MWVP15-5Bkqb3	0.0245	NA
5A	Sand	MWVP15-5Bkq2b3	0.0245	NA
D09-01	Sandy Loam	MWVP5-Avk	0.0300	NA
D11-08	Sandy Loam	MWVP5-Bwk	0.0141	NA
D10-04	Sandy Loam	MWVP5-Bwk2	0.0361	NA
D10-04	Sandy Loam	MWVP5-2Bwkb	0.0141	NA
4-1057	Loamy Sand	MWVP5-3Btkqmb2	0.0300	NA
h0-073	Loamy Sand	MWVP5-3Btkqm2b2	0.0806	NA
5-0004	Sand	MWVP5-3Bkqb2	0.0283	NA
h0-082	Loamy Sand	MWVP5-4Bkqb3	0.0332	NA
3-0682	Sand	MWVP5-4Bkq2b3	0.0141	NA
5-0004	Sand	MWVP5-4BCkqb3	0.0283	NA
h0-082	Loamy Sand	MWVP5-5Bkqb4	0.0436	NA
3-0649	Loam	MWVP9-Av	0.0787	NA
NO MATCH	NA	MWVP9-Bt	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
NO MATCH	NA	MWVP9-2Bt	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
3-0647	Loamy Sand	MWVP9-3Btkq	0.0490	NA
h0-082	Loamy Sand	MWVP9-3Bkq	0.0332	NA
4-0855	Sand	MWVP9-4Bkqi	0.0245	NA
3-0682	Sand	MWVP9-4Bkq2	0.0141	NA
h0-082	Loamy Sand	MWVP9-5Kq	0.0141	NA
4-0973	Loamy Sand	MWVP9-6BCkq	0.0000	NA
5-0004	Sand	MWVP9-7Bkqb	0.0283	NA
3-0649	Loam	MWVP8-Av	0.0490	NA

Table A-2. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 2 (Continued)

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
4-1058	Loam	MWVP8-BAtj	0.1005	NA
NO MATCH	NA	MWVP8-Bt	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
3-0649	Loam	MWVP8-Btqk	0.1044	NA
h0-073	Loamy Sand	MWVP8-BCkq	0.0424	NA
h0-073	Loamy Sand	MWVP8-CBkq	0.0592	NA
5-0007	Sand	MWVP8-Ck	0.0141	NA
3-0682	Sand	MWVP8-2Btkqb	0.0141	NA
2-2230	Loamy Sand	MWVP8-2CBkb	0.0300	NA
3-0649	Loam	MWVP24-Av	0.0510	NA
D02-16	Sandy Loam	MWVP24-Btk	0.0510	NA
NO MATCH	NA	MWVP24-2Btkq	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
3-0647	Loamy Sand	MWVP24-2Btkq2	0.0510	NA
5-0007	Sand	MWVP24-2Bkq1	0.0300	NA
5-0007	Sand	MWVP24-2Bkq2	0.0100	NA
4-0855	Sand	MWVP24-3Cq	0.0424	NA
241-AP-6	Loamy Sand	MWVP24-3Bkqb	0.0374	NA
3-0649	Loam	MWVP22-Avk	0.0748	NA
D05-03	Sandy Loam	MWVP22-2Btjk	0.0616	NA
h0-073	Loamy Sand	MWVP22-2Btkq	0.0648	NA
3-0647	Loamy Sand	MWVP22-2Bkq	0.0616	NA
h0-085	Loamy Sand	MWVP22-2Bkq2	0.0374	NA
5-0004	Sand	MWVP22-3Ckq	0.0424	NA
4-0644	Loamy Sand	MWVP20-Avj	0.0141	NA
3-0651	Loamy Sand	MWVP20-ABvk	0.1338	NA
NO MATCH	NA	MWVP20-2Bwk	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
3-0651	Loamy Sand	MWVP20-2Btkq	0.0510	NA
3-0651	Loamy Sand	MWVP20-2Btkq2	0.0927	NA

Table A-2. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 2 (Continued)

Hanford Sample Number	USDA Soil Classification of Hanford Sample	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
NO MATCH	NA	MWVP20-3Bkq	NO MATCH	Justification for no match: very low silt fraction, no corresponding Hanford match.
3-0682	Sand	MWVP20-4Bkqy	0.0283	NA
4-0973	Loamy Sand	MWVP20-5Btkqb	0.0100	NA
3-0682	Sand	MWVP20-6BCkqb	0.0283	NA
D02-10	Sandy Loam	MWVP6-Avk	0.0283	NA
D12-14	Sandy Loam	MWVP6-2Btjkq	0.0490	NA
D02-10	Sandy Loam	MWVP6-2Btkq	0.0245	NA
D02-10	Sandy Loam	MWVP6-2Btjkq12	0.0141	NA
D11-06	Sandy Loam	MWVP6-2Btjkq22	0.0173	NA
2-2230	Loamy Sand	MWVP6-3Kqb	0.0141	NA
4-0855	Sand	MWVP6-3Bkqb	0.0141	NA
2-2230	Loamy Sand	MWVP6-3Bkq2b	0.0200	NA
5-0005	Sandy Loam	MWVP6-3BCkqb	0.0424	NA
5-0004	Sand	MWVP6-4Bkqb2	0.0500	NA
5-0004	Sand	MWVP6-4Bkq2b2	0.0361	NA
241-AP-3	Sand	MWVP6-4CBkqb2	0.0283	NA
241-AP-6	Loamy Sand	FW-5-A	0.0224	NA
3-0647	Loamy Sand	FW-5-AB	0.0458	NA
3-0647	Loamy Sand	FW-5-Btk	0.0500	NA
4-0644	Loamy Sand	FW-5-2Btkv	0.0000	NA
h0-082	Loamy Sand	FW-5-2Btqmkb	0.0200	NA
5-0004	Sand	FW-5-2Kqb	0.0374	NA
h0-082	Loamy Sand	SWG-1-Bkq	0.0224	NA
3-0651	Loamy Sand	SWG-1-CBk	0.0361	NA
4-0855	Sand	SWG-1-2Btjb	0.0100	NA
4-0855	Sand	SWG-1-3Bkqmb	0.0224	NA
h0-082	Loamy Sand	SWG-1-3CBkb	0.0245	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit2_HydProps_5-1-06.xls*, worksheet 'MatchUncertainty'.

NOTE: The letter "h" is added to beginning of some Hanford sample identifications to facilitate the matching of textural data.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

Table A-3. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 3

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D09-05	Sandy Loam	PWT1-30m	0.0245	NA
3-0651	Loamy Sand	PWT2-210m	0.0787	NA
D05-03	Sandy Loam	PWT3-60m	0.0510	NA
D05-03	Sandy Loam	PWT4-240m	0.0648	NA
3-0647	Loamy Sand	PWT5-0m	0.0283	NA
3-0647	Loamy Sand	PWT6-30m	0.0141	NA
0-073	Loamy Sand	PWT5-60m	0.0424	NA
19A	Sandy Loam	SWT1-0m	0.0141	NA
D02-16	Sandy Loam	SF16-1	0.0424	NA
3-0651	Loamy Sand	SF16-2	0.1208	NA
D04-04	Sandy Loam	SF16-3	0.0510	NA
241-AP-6	Loamy Sand	SF17-1	0.0224	NA
3-0647	Loamy Sand	SF17-2	0.0374	NA
3-0647	Loamy Sand	SF17-3	0.0374	NA
5-0001	Loamy Sand	SF18-1	0.0583	NA
0-085	Loamy Sand	SF18-2	0.0510	NA
3-0682	Sand	SF18-3	0.0374	NA
5-0005	Sandy Loam	SF30-1	0.0490	NA
5-0002	Loamy Sand	SF30-2	0.0200	NA
5-0001	Loamy Sand	SF30-3	0.0245	NA
4-0644	Loamy Sand	SF25-1	0.0245	NA
241-AP-6	Loamy Sand	SF25-2	0.0224	NA
241-AP-6	Loamy Sand	SF25-3	0.0300	NA
D04-04	Sandy Loam	SF11-1	0.0990	NA
D04-04	Sandy Loam	SF11-2	0.0748	NA
D05-03	Sandy Loam	SF11-3	0.0510	NA
5-0002	Loamy Sand	U5DR1	0.0245	NA
3-0647	Loamy Sand	MWVP10-A	0.0283	NA
241-AP-6	Loamy Sand	MWVP10-Bw	0.0100	NA
0-073	Loamy Sand	MWVP10-Bwk	0.0500	NA
3-0682	Sand	MWVP10-2BCk	0.0374	NA
4-0644	Loamy Sand	MWVP10-2CBk	0.0141	NA
3-0651	Loamy Sand	MWVP10-3Btkqb	0.0748	NA
0-085	Loamy Sand	MWVP10-3Bkqb	0.0490	NA
5-0004	Sand	MWVP10-3CBkb	0.0374	NA
5-0005	Sandy Loam	PW1	0.0224	NA
3-0647	Loamy Sand	PW2	0.0374	NA
5-0005	Sandy Loam	PW3	0.0424	NA
241-AP-6	Loamy Sand	PW4	0.0592	NA
5-0005	Sandy Loam	PW5	0.0283	NA

Table A-3. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 3 (Continued)

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
NO MATCH	NA	SW1	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
NO MATCH	NA	SW2	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
D05-03	Sandy Loam	SW3	0.0510	NA
NO MATCH	NA	SW4	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
NO MATCH	NA	SW5	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
0-101	Sand	DHW1	0.0424	NA
5-0004	Sand	DHW2	0.0224	NA
5-0004	Sand	DHW3	0.0510	NA
0-085	Loamy Sand	DHW4	0.0141	NA
5-0004	Sand	DHW5	0.0374	NA
5-0004	Sand	DHW6	0.0490	NA
5-0004	Sand	DHW7	0.0539	NA
3-0682	Sand	DHW8	0.0361	NA
5-0005	Sandy Loam	DHW9	0.0100	NA
3-0647	Loamy Sand	DHW10	0.0510	NA
D05-03	Sandy Loam	DHW11	0.0781	NA
D09-05	Sandy Loam	DHW12	0.0283	NA
D09-05	Sandy Loam	DHW13	0.0224	NA
D11-08	Sandy Loam	DHW14	0.0141	NA
3-0651	Loamy Sand	WT1	0.1131	NA
241-AP-6	Loamy Sand	WT2	0.0224	NA
3-0651	Loamy Sand	WT3	0.0787	NA
5-0005	Sandy Loam	NCWTX1-A0	0.0000	NA
D05-03	Sandy Loam	NCWTX1-Bwk	0.0648	NA
241-AP-6	Loamy Sand	NCWTX1-BCk	0.0361	NA
0-085	Loamy Sand	NCWTX1-Ck	0.0490	NA
241-AP-6	Loamy Sand	NCWTX1-2Btkqb1	0.0458	NA

Table A-3. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 3 (Continued)

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
5-0005	Sandy Loam	NCWTX1-2Btkqb2	0.0500	NA
4-0644	Loamy Sand	NCWTX1-2BCkqb	0.0224	NA
5-0005	Sandy Loam	NCWTX1-3Btqb	0.0245	NA
5-0006	Loamy Sand	MWV7-1	0.0173	NA
4-0644	Loamy Sand	MWV7-2	0.0374	NA
3-0651	Loamy Sand	MWV7-3	0.0883	NA
3-0647	Loamy Sand	MWV7-4	0.0141	NA
3-0647	Loamy Sand	MWV7-5	0.0141	NA
5-0006	Loamy Sand	U5DR1	0.0436	NA
0-085	Loamy Sand	U5DR2	0.0245	NA
0-085	Loamy Sand	U5DR3	0.0141	NA
0-085	Loamy Sand	U5DR4	0.0141	NA
D05-03	Sandy Loam	NCW-TT1-A	0.0141	NA
D04-04	Sandy Loam	NCW-TT1-Bw	0.0141	NA
D11-08	Sandy Loam	MCW-TT1-BCk1	0.0510	NA
3-0688	Sandy Loam	NCW-TT1-BCk2	0.0374	NA
241-AP-6	Loamy Sand	NCW-TT1-2CBk	0.0300	NA
241-AP-6	Loamy Sand	NCW-TT1-3CBk	0.0500	NA
5-0002	Loamy Sand	MWVP14-A	0.0332	NA
0-073	Loamy Sand	MWVP14-Bw	0.0245	NA
4-0855	Sand	MWVP14-CBk	0.0000	NA
4-0644	Loamy Sand	MWVP14-2CBk	0.0141	NA
5-0004	Sand	MWVP14-3CBk1	0.0374	NA
4-0855	Sand	MWVP14-3CBk2	0.0000	NA
0-101	Sand	MWVP14-4Btkqb1	0.0592	NA
0-085	Loamy Sand	MWVP14-5Btqb2	0.0173	NA
241-AP-6	Loamy Sand	MWVP7-A	0.0245	NA
3-0647	Loamy Sand	MWVP7-Bw	0.0173	NA
3-0651	Loamy Sand	MWVP7-Bwk	0.0728	NA
241-AP-6	Loamy Sand	MWVP7-Bwk2	0.0300	NA
25A	Loamy Sand	MWVP7-Bk	0.0000	NA
5-0001	Loamy Sand	MWVP7-2Bkqb	0.0316	NA
5-0004	Sand	MWVP7-2Bkq2b	0.0100	NA
5-0004	Sand	MWVP7-2Bkq3b	0.0000	NA
5-0002	Loamy Sand	MWVP7-2Cqb	0.0224	NA
241-AP-6	Loamy Sand	MWVP7-3Bkqb2	0.0332	NA
5-0002	Loamy Sand	MWVP21-A	0.0539	NA
4-0644	Loamy Sand	MWVP21-Bw	0.0141	NA
0-085	Loamy Sand	MWVP21-2BCk	0.0224	NA
5-0004	Sand	MWVP21-2BCk2	0.0490	NA
3-0682	Sand	MWVP21-3Bkqb	0.0245	NA
3-0682	Sand	MWVP21-4Btjkqb	0.0224	NA

Table A-3. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 3 (Continued)

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
3-0682	Sand	MWVP21-5Bkqb	0.0374	NA
5-0004	Sand	PW6	0.0000	NA
241-AP-6	Loamy Sand	PW7	0.0224	NA
3-0682	Sand	PW8	0.0374	NA
4-0855	Sand	PW9	0.0000	NA
5-0002	Loamy Sand	PW10	0.0332	NA
0-073	Loamy Sand	PW11	0.0648	NA
241-AP-6	Loamy Sand	DuW1	0.0361	NA
241-AP-6	Loamy Sand	DuW2	0.0200	NA
5-0001	Loamy Sand	DuW3	0.0316	NA
3-0647	Loamy Sand	DuW4	0.0141	NA
3-0647	Loamy Sand	DuW5	0.0141	NA
3-0651	Loamy Sand	DuW6	0.0748	NA
241-AP-6	Loamy Sand	DuW7	0.0332	NA
241-AP-6	Loamy Sand	DuW8	0.0141	NA
0-073	Loamy Sand	DuW9	0.0374	NA
3-0651	Loamy Sand	DuW10	0.1393	NA
D07-04	Sandy Loam	DuW11	0.0283	NA
3-0651	Loamy Sand	DuW12	0.1208	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit3_HydProps_5-1-06.xls*, worksheet 'MatchUncertainty'.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

Table A-4. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 4

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
99A	Sand	PWT1-0m	0.0141	NA
3-0647	Loamy sand	PWT3-30m	0.0566	NA
D09-05	Sandy loam	SWT2-30m	0.0283	NA
5-0006	Loamy sand	SF6-1	0.0141	NA
3-0647	Loamy sand	SF6-2	0.0490	NA
3-0689	Sandy loam	SF6-3	0.0245	NA
46A	Sand	SF10-1	0.0141	NA
99A	Sand	SF10-3	0.0141	NA
3-0682	Sand	SF12-1	0.0424	NA
3-0682	Sand	SF12-2	0.0283	NA
4-0855	Sand	SF12-3	0.0141	NA
4-0855	Sand	SF23-1	0.0283	NA
99A	Sand	SF23-2	0.0141	NA
5-0006	Loamy sand	SF23-3	0.0566	NA
241-AP-3	Sand	DBL40Mile01	0.0141	NA

Table A-4. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 4 (Continued)

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
NO MATCH	NA	DBL40Mile02	NO MATCH	Fraction of sand, silt, and clay not available
3-0682	Sand	MWV1-1	0.0141	NA
0-104	Sand	MWV1-2	0.0100	NA
99A	Sand	MWV1-3	0.0000	NA
99A	Sand	MWV1-4	0.0141	NA
241-AP-3	Sand	MWV1-5	0.0224	NA
46A	Sand	MWV2-1	0.0283	NA
99A	Sand	MWV2-2	0.0141	NA
46A	Sand	MWV2-3	0.0000	NA
46A	Sand	MWV2-4	0.0100	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit4_HydProps_5-1-06.xls*, worksheet 'MatchUncertainty'.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

Table A-5. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 5

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D05-03	Sandy loam	PWT1-90m	0.0616	NA
5-0005	Sandy loam	PWT1-150m	0.0374	NA
241-AP6	Loamy sand	PWT1-180m	0.0361	NA
5-0005	Sandy loam	PWT1-210	0.0141	NA
241-AP6	Loamy sand	PWT1-240m	0.0100	NA
D05-03	Sandy loam	PWT2-60m	0.0787	NA
D05-03	Sandy loam	PWT2-120m	0.0490	NA
3-0689	Sandy loam	PWT2-150m	0.0141	NA
D02-16	Sandy loam	PWT3-180m	0.0490	NA
5-0005	Sandy loam	PWT3-210m	0.0000	NA
3-0688	Sandy loam	PWT3-240m	0.0245	NA
241-AP6	Loamy sand	PWT3-270	0.0361	NA
5-0005	Sandy loam	PWT4-0m	0.0245	NA
3-0689	Sandy loam	PWT4-30m	0.0141	NA
241-AP6	Loamy sand	PWT4-90m	0.0332	NA
5-0005	Sandy loam	PWT4-180m	0.0374	NA
241-AP6	Loamy sand	PWT5-120m	0.0100	NA
5-0005	Sandy loam	PWT5-150m	0.0283	NA
5-0005	Sandy loam	PWT5-210m	0.0424	NA
5-0005	Sandy loam	PWT5-240m	0.0141	NA
241-AP6	Loamy sand	PWT5-270m	0.0361	NA
5-0005	Sandy loam	PWT6-90m	0.0424	NA

Table A-5. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 5 (Continued)

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D05-03	Sandy loam	PWT6-120m	0.0490	NA
241-AP6	Loamy sand	PWT6-180	0.0224	NA
241-AP6	Loamy sand	PWT6-240m	0.0412	NA
5-0005	Sandy loam	PWT6-270m	0.0490	NA
5-0005	Sandy loam	SWT1-60m	0.0283	NA
5-0005	Sandy loam	SWT1-90m	0.0141	NA
241-AP6	Loamy sand	SWT1-120m	0.0458	NA
5-0005	Sandy loam	SWT1-150m	0.0245	NA
D05-03	Sandy loam	SWT2-60m	0.0735	NA
5-0005	Sandy loam	SWT2-210m	0.0141	NA
NO MATCH	NA	SWT2-240m	NO MATCH	Justification for no match: zero clay fraction, no corresponding Hanford match.
5-0005	Sandy loam	SWT2-300m	0.0141	NA
5-0005	Sandy loam	SWT2-330m	0.0141	NA
D08-15	Sandy loam	SF1-1	0.0374	NA
D04-04	Sandy loam	SF1-2	0.0283	NA
D08-15	Sandy loam	SF1-3	0.0374	NA
D08-15	Sandy loam	SF2-1	0.0510	NA
D02-16	Sandy loam	SF2-2	0.0245	NA
D02-16	Sandy loam	SF2-3	0.0374	NA
D02-16	Sandy loam	SF3-1	0.0374	NA
D02-16	Sandy loam	SF3-3	0.0374	NA
D02-16	Sandy loam	SF4-1	0.0374	NA
NO MATCH	NA	SF4-2	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
NO MATCH	NA	SF4-3	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
NO MATCH	NA	SF5-1	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
241-AP6	Loamy sand	SF5-2	0.0361	NA
D05-03	Sandy loam	SF5-3	0.1068	NA

Table A-5. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 5 (Continued)

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for “No Match”
D02-16	Sandy loam	SF24-1	0.0141	NA
NO MATCH	NA	SF24-2	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
D02-16	Sandy loam	SF24-3	0.0490	NA
D05-03	Sandy loam	SF26-1	0.0141	NA
D05-03	Sandy loam	SF26-2	0.0283	NA
D05-03	Sandy loam	SF26-3	0.0510	NA
5-0005	Sandy loam	SF19-1	0.0424	NA
D12-14	Sandy loam	SF19-2	0.0490	NA
3-0688	Sandy loam	SF19-3	0.0283	NA
5-0005	Sandy loam	SF20-1	0.0424	NA
5-0005	Sandy loam	SF20-2	0.0141	NA
5-0005	Sandy loam	SF20-3	0.0141	NA
3-0689	Sandy loam	SF21-1	0.0245	NA
5-0005	Sandy loam	SF21-2	0.0245	NA
D05-03	Sandy loam	SF21-3	0.0510	NA
D05-03	Sandy loam	SF22-1	0.0648	NA
D05-03	Sandy loam	SF22-2	0.0648	NA
3-0689	Sandy loam	SF22-3	0.0374	NA
3-0688	Sandy loam	YC4	0.0424	NA
3-0688	Sandy loam	YC5	0.0374	NA
3-0688	Sandy loam	YC6	0.0141	NA
5-0005	Sandy loam	YC7	0.0424	NA
D11-06	Sandy loam	YC8	0.0000	NA
5-0005	Sandy loam	YC9	0.0141	NA
D05-03	Sandy loam	YC10	0.0510	NA
3-0688	Sandy loam	YC11	0.0245	NA
D05-03	Sandy loam	YC12	0.0648	NA
3-0689	Sandy loam	WT4	0.0283	NA
D11-08	Sandy loam	WT5	0.0500	NA
5-0005	Sandy loam	WT6	0.0000	NA
2-2230	Loamy sand	MWV6-1	0.0424	NA
D11-06	Sandy loam	MWV6-2	0.0141	NA
2-2230	Loamy sand	MWV6-3	0.0548	NA
D11-06	Sandy loam	MWV6-4	0.0283	NA
D07-04	Sandy loam	MWV6-5	0.0141	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit5_HydProps_5-1-06.xls*, worksheet ‘MatchUncertainty’.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

Table A-6. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 7

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
D05-03	Sandy loam	SF7-1	0.0374	NA
D05-03	Sandy loam	SF7-2	0.0510	NA
D02-16	Sandy loam	SF7-3	0.0141	NA
NO MATCH	NA	SF8-1	NO MATCH	Justification for no match: low sand fraction with equally high silt and clay fractions, no corresponding Hanford match.
NO MATCH	NA	SF8-2	NO MATCH	Justification for no match: low sand fraction with equally high silt and clay fractions, no corresponding Hanford match.
D02-16	Sandy loam	SF8-3	0.0141	NA
D02-16	Sandy loam	SF9-1	0.0283	NA
NO MATCH	NA	SF9-2	NO MATCH	Justification for no match: low sand fraction with high silt and clay fractions, no corresponding Hanford match.
D02-16	Sandy loam	SF9-3	0.0424	NA
D11-08	Sandy loam	CP1	0.0141	NA
D08-15	Sandy loam	CP2	0.0245	NA
D10--04	Sandy loam	CP3	0.0141	NA
D05-03	Sandy loam	CP4	0.0458	NA
D05-03	Sandy loam	CP5	0.0283	NA
NO MATCH	NA	CP6	NO MATCH	Justification for no match: low sand fraction with equally high silt and clay fractions, no corresponding Hanford match.
241-AP6	Loamy Sand	CP7	0.0173	NA
D07-04	Sandy loam	CP8	0.0374	NA
D05-03	Sandy loam	CP9	0.0374	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit7_HydProps_5-1-06.xls*, worksheet 'MatchUncertainty'.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

Table A-7. Euclidean Distances in Three-Dimensional Space for Matches between Hanford and Yucca Mountain Soil Samples Based on Fraction of Sand, Silt, and Clay: Soil Unit 9

Hanford Sample Number	Hanford Sample USDA Soil Classification	YMP Sample Number	Euclidean Distance (dimensionless)	Reason for "No Match"
5-0005	Sandy loam	PWT1-60m	0.037416574	NA
5-0005	Sandy loam	PWT2-180m	0.014142136	NA
D05-03	Sandy loam	PWT4-210m	0.014142136	NA
D05-03	Sandy loam	PWT5-30m	0.050990195	NA
D05-03	Sandy loam	PWT5-60m	0.024494897	NA
5-0005	Sandy loam	SWT1-30m	0.037416574	NA
5-0005	Sandy loam	SF15-1	0.014142136	NA
5-0005	Sandy loam	SF15-2	0.037416574	NA
5-0005	Sandy loam	SF15-3	0.037416574	NA
D09-01	Sandy loam	WT7	0.024494897	NA
NO MATCH	NA	WT8	NO MATCH	Justification for no match: low sand value and high silt value, no corresponding Hanford match.
D07-04	Sandy loam	WT9	0.014142136	NA
D08-15	Sandy loam	NRG5T3-Bw	0.024494897	NA
D07-04	Sandy loam	NRG5T3-Btk	0.037416574	NA
5-0005	Sandy loam	NRG5T3-Btkm1	0.037416574	NA
D05-03	Sandy loam	NRG5T3-Btkm2	0.037416574	NA
241-AP6	Loamy sand	NRG5T3-Ckqm1	0.03	NA
5-0005	Sandy loam	NRG5T3-Ckqm2	0.037416574	NA
D05-03	Sandy loam	NRG5T4-Bw	0.064807407	NA
D05-03	Sandy loam	NRG5T1-Bt	0.014142136	NA
5-0005	Sandy loam	NRG5T1-Btk	0.033166248	NA
241-AP6	Loamy sand	NRG5T1-Ckm1	0.01	NA
5-0005	Sandy loam	NRG5T1-Ckm2	0.028284271	NA
5-0005	Sandy loam	NRG5T2-Bw	0.042426407	NA
5-0005	Sandy loam	NRG5T2-Btk	0.050990195	NA
241-AP6	Loamy sand	NRG5T2-Ckm	0.053851648	NA

Source: Output DTN: MO0605SEPDEVSH.002, *SoilUnit9_HydProps_5-1-06.xls*, worksheet 'MatchUncertainty'.

NA = not applicable; USDA = U.S. Department of Agriculture; YMP = Yucca Mountain Project.

APPENDIX B

BACKGROUND INFORMATION USED TO GENERATE DATA FOR YMP GROUP METHOD CORROBORATION

BACKGROUND INFORMATION USED TO GENERATE DATA FOR YMP GROUP METHOD CORROBORATION

The method used to derive Yucca Mountain soil hydraulic properties is corroborated with two alternative pedotransfer functions (PTFs): Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and ROSETTA (Schaap et al. 1998 [DIRS 177199] and 2001 [DIRS 176006]), a neural-network computer program developed at the United States USDA Salinity Laboratory. These calculations are documented in the non-Q DTN: MO0608SPAPEDOT.000 and the comparison between methods are discussed in Section 6.4.5.

DTN: MO0608SPAPEDOT.000 documents the calculations developed with the non-Q code ROSETTA (Schaap et al. 1998 [DIRS 177199]) that were prepared under the guidance of *Technical Work Plan For: Infiltration Model Assessment, Revision, and Analyses of Downstream Impacts* (BSC 2006 [DIRS 177492], Sections 1.1.6, 4.2, and 8.2) and under the requirements of *Augmented Quality Assurance Program* (DOE 2004 [DIRS 171341]). It also documents the calculations developed with the PTF from Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]). Table B-1 is reproduced from DTN: MO0608SPAPEDOT.000 and provides a summary of the data sources used in the analysis.

Table B-1. Summary of Inputs used in DTN: MO0608SPAPEDOT.000

Data Source:	Parameters:	File/Worksheet:
DTN: MO0605SEPALTRN.000 “Alternative Soil Units, Hydraulic Parameters, and Associated Statistics for Infiltration Modeling At Yucca Mountain, NV”	Permanent wilting point at −60 bar (cm^3/cm^3) Moisture content at −0.1 bar (cm^3/cm^3) Moisture content at −0.33 bar (cm^3/cm^3) Holding capacity at −0.1 bar (cm^3/cm^3) Holding capacity at −0.1 bar (cm^3/cm^3) Saturated hydraulic conductivity (cm/s) Saturated water content, theta S (cm^3/cm^3)	*AllSoilsFC1-10and1-3Bar_5-30-06.xls*/ ‘HydraulicPropandStatistics’
DTN: MO0512SPASURFM.002 “Fy94 and Fy95 Laboratory Measurements of Physical Properties of Surficial Materials at Yucca Mountain, Nevada (Part I)”	Soil texture (percent sand, silt, and clay) Rock fragment content Bead cone bulk density Total porosity	*YMPSoilProperties_PartI_ALL94andALL295.xls*/ ‘ALL94’/ ‘ALL295’
DTN: GS031208312211.001 “Fy95 Laboratory Measurements of Physical Properties of Surficial Material at Yucca Mountain, Part II”	Soil texture (percent sand, silt, and clay) Rock fragment content Bead cone bulk density Total porosity	*ALL395.xls*/’ALL395’

Source: DTN: MO0608SPAPEDOT.000.

In DTN: MO0608SPAPEDOT.000, calculations using the Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) regression equation are performed in the ‘AllSoilUnits Data’, ‘SoilUnit1 Data’, ‘SoilUnits2-6 Data’, ‘SoilUnits3-4 Data’ and ‘SoilUnits5-7-9 Data’, worksheets. The Rawls and Brakensiek regression coefficients are listed in the ‘COEF’ worksheet. The Cronican and Gribb (2004 [DIRS 177039]) regression equation is used for samples containing greater than 70% sand.

In Table B-2, reproduced from DTN: MO0608SPAPEDOT.000, the ROSETTA input and output data are listed. The output data are also provided in the 'RosettaOutput' worksheets within each Excel® workbooks in DTN: MO0608SPAPEDOT.000. The ROSETTA input and output data are also entered in the Excel® workbooks in DTN: MO0608SPAPEDOT.000, where unit conversions are performed on the ROSETTA output data. Descriptive statistics and comparisons between methods are contained in the 'AllSoilUnits Statistics', 'SoilUnit1 Statistics', 'SoilUnit2-6 Statistics', 'SoilUnit3-4 Statistics', and 'SoilUnit5-7-9 Statistics' worksheets. In DTN: MO0608SPAPEDOT.000, the means are compiled and plotted for visual comparison in *Summary_MethodCorroboration_August31_2006.xls*. In Table B-3, reproduced from DTN: MO0608SPAPEDOT.000, the analysis files are listed.

Table B-2. ROSETTA Input/Output Files from DTN: MO0608SPAPEDOT.000

ROSETTA Input Files:	**ROSETTA Output Files:**
YMPAllSoilUnitsInputData.txt	*YMPAllSoilUnitsOutput.txt & YMPAllSoilUnitsOutputBD.txt*
YMPSoilUnit1InputData.txt	*YMPSoilUnit1Output.txt & YMPSoilUnit1OutputBD.txt*
YMPSoilUnit2-6InputData.txt	*YMPSoilUnit2-6Output.txt & YMPSoilUnit2-6OutputBD.txt*
YMPSoilUnit3-4InputData.txt	*YMPSoilUnit3-4Output.txt & YMPSoilUnit3-4OutputBD.txt*
YMPSoilUnit5-7-9InputData.txt	*YMPSoilUnit5-7-9Output.txt & YMPSoilUnit5-7-9OutputBD.txt*

Source: DTN: MO0608SPAPEDOT.000.

Table B-3. Analysis File Descriptions

File:	**Description:**
AllSoilUnits_Method-Verification_August31_2006.xls	Pedotransfer function calculations and comparison for all base case soil units.
SoilUnit1_Method-Corroboration_August31_2006.xls	Pedotransfer function calculations and comparisons for Soil Unit 1.
SoilUnit2-6_Method-Corroboration_August31_2006.xls	Pedotransfer function calculations and comparisons for combined Soil Units 2 and 6.
SoilUnit3-4_Method-Corroboration_August31_2006.xls	Pedotransfer function calculations and comparisons for combined Soil Units 3 and 4.
SoilUnit5-7-9_Method-Corroboration_August31_2006.xls	Pedotransfer function calculations and comparisons for combined Soil Units 5, 7, and 9.
Summary_MethodCorroboration_August31_2006.xls	Compiled soil parameter values and bar graphs for visual comparison.

Source: DTN: MO0608SPAPEDOT.000.

APPENDIX C

BACKGROUND INFORMATION USED TO GENERATE DATA FOR NYE COUNTY METHOD CORROBORATION

BACKGROUND INFORMATION USED TO GENERATE DATA FOR NYE COUNTY METHOD CORROBORATION

The method used to derive Yucca Mountain soil hydraulic properties is corroborated with Nye County soils data obtained from the United States Department of Agriculture (USDA) National Resource Conservation Service Soil Survey Laboratory Soil Characterization Database [DIRS 177088] and two alternative pedotransfer functions (PTFs): Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]) and ROSETTA (Schaap et al. 1998 [DIRS 177199] and 2001 [DIRS 176006]). The corroborative soil hydraulic parameter values were derived by matching soil textural data (i.e., percentages of silt, sand, and clay) and rock fragment content from the Nye County data to an analogous database that contains soil texture and hydraulic parameter values for soils similar to those at Yucca Mountain *Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site* (Khaleel and Freeman 1995 [DIRS 175734], Appendix A and B).

The Nye County derived soil hydraulic properties were compared to soil hydraulic properties developed from two alternative pedotransfer functions (PTFs): one developed by Rawls and Brakensiek (Rawls and Brakensiek 1985) [DIRS 177045], and ROSETTA (Schaap et al. 2001 [DIRS 176006]), a neural-network computer program developed at the United States USDA Salinity Laboratory. Additionally, soil moisture retention data at −10 kPa (−0.10 bar) and −33 kPa (−0.33 bar) were available in the Nye County Data set, which were compared with the derived moisture contents at −0.10 and −0.33 bar.

DTN: MO0608SPANYECT.000 documents the calculations developed with the non-Q code ROSETTA (Schaap et al. 1998 [DIRS 177199]) that were prepared under the guidance of *Technical Work Plan For: Infiltration Model Assessment, Revision, and Analyses of Downstream Impacts* (BSC 2006 [DIRS 177492], Sections 1.1.6, 4.2, and 8.2) and under the requirements of *Augmented Quality Assurance Program* (DOE 2004 [DIRS 171341]). It also documents the calculations developed with the PTF from Rawls and Brakensiek (Rawls and Brakensiek 1985 [DIRS 177045]). Table C-1 is reproduced from DTN: MO0608SPANYECT.000 and provides a summary of the data sources used in the analysis.

Table C-1. Summary of Inputs used in DTN: MO0608SPANYECT.000

Data Report	Parameter	Location in Data Report
Primary Characterization Report: *NyeCounty_PrimaryData_June2006.htm* Nye County Data Sets: NRCS Soil Survey Laboratory (http://ssldata.nrcs.usda.gov/) [DIRS 176439]	Soil texture (percent clay, silt, sand)	PSDA & Rock Fragments Columns: -1-, -2-, and -3-
	Rock fragments	PSDA & Rock Fragments Column: -17-
	Oven dry bulk density	Bulk Density & Moisture Column: -2-
	Water Content at −10, −33, and −1,500 kPa	Bulk Density & Moisture Columns: -5-, -6-, and -7-
Supplementary Characterization Report: *NyeCounty_SupplementData_June2006.htm* Nye County Data Sets: NRCS Soil Survey Laboratory (http://ssldata.nrcs.usda.gov/) [DIRS 177049]	Whole soil void ratio	Tier 2 Column: -49-
Hanford Database: Khaleel R. and Freeman E.J. 1995, “Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford site.” [DIRS 175734]	Soil texture for specified Hanford samples (percent sand, silt, clay and rock fragments)	Appendix A

Source: DTN: MO0608SPANYECT.000.

Nye County Data Matched to Hanford Data Set (*NyeCounty_Hanford_DataMatch_August22_2006.xls*):

In DTN: MO0608SPANYECT.000, soils data in the Nye County reports are organized by pedon number and layer. Each Nye County layer used in the analysis is listed in the ‘HanfordMatchtoNyeCo’ worksheet in DTN: MO0608SPANYECT.000. Each layer represents one sample. The Nye County layer (sample) matches to Hanford database textural data is performed in the ‘HanfordMatchtoNyeCo’ worksheet, and rock fragment corrections were performed in the ‘RockFragCorrection’ worksheet. The resulting data are compiled in DTN: MO0608SPANYECT.000 in the following worksheets:

- “CompiledParameters” contains the complete list of Nye County layers; S_LS_SL, contains the Nye County layers representing USDA soil classes sand, loamy sand, and sandy loam
- “Sand” contains the Nye County layers representing the USDA soil class sand
- “LoamySand” contains the Nye County layers representing the USDA soil class loamy sand
- “SandyLoam” contains the Nye County layers representing USDA soil class sandy loam.

Alternative Pedotransfer Functions (*NyeCounty_MethodCorroboration_August1_2006.xls*): In DTN: MO0608SPANYECT.000, calculations using the Rawls and Brakensiek regression equation are performed in the 'NyeCountyData' worksheet. The Rawls and Brakensiek regression coefficients are listed in the 'COEF' worksheet. The Cronican and Gribb regression equation is used for samples containing > 70% sand. Inputs from the Nye County data include percent sand, percent clay, and total calculated porosity. Total calculated porosity was calculated from Nye County void ratio in *NyeCounty_Hanford_DataMatch_August22_2006.xls*, 'HanfordMatchtoNyeCo' worksheet.

In DTN: MO0608SPANYECT.000, ROSETTA input and output data are provided in *NyeCountyInputData.txt* and *NyeCountyOutput.txt*, respectively. The output data are also provided in the 'RosettaOutput' worksheet. The ROSETTA input and output data are also entered in the 'NyeCountyData' worksheet where unit conversions are performed on the ROSETTA output data.

In DTN: MO0608SPANYECT.000, the results from the two alternative pedotransfer function methods are summarized by USDA classification in the 'NyeCountyData_S_LS_SL', 'NyeCountyData_Sand', 'NyeCountyData_LoamySand', and 'NyeCountyData_SandyLaom' worksheets, while the 'NyeCounty_Complete' worksheet summarizes the results for all Nye County layers (samples). The descriptive statistics and comparisons among parameters are presented in the 'CompleteNyeCountyStats', 'S_LS_SLNyeCountyStats', 'Sand_ NyeCountyStats', 'LoamySand_NyeCountyStats', and 'SandyLoam_NyeCountyStats' worksheets. The Nye County – Hanford matched results were copied in from *NyeCounty_Hanford_DataMatch_August22_2006.xls*. The parameter means are plotted on bar graphs in the worksheet 'CompareMeans'.

Moisture Retention Curves (*MoistureRetentionCurve_MethodCorroboration_August22_ 2006.xls*):

In DTN: MO0608SPANYECT.000, moisture retention curves for Hanford derived data were plotted using the van Genuchten equation with the Mualem model (m = 1-1/n) using Equations 2 and 3 from van Genuchten (1980 [DIRS 100610], Equations 2 and 3).

In DTN: MO0608SPANYECT.000 moisture retention curves were formed by using the van Genuchten parameters (alpha, n, theta R, and theta S), which were derived from the Nye County – Hanford database matches (*NyeCounty_Hanford_DataMatch_August22_2006.xls*). The curves were formed from the Nye County layer data representing the USDA soil classes sand, loamy sand, and sandy loam. The Nye county water content data at −10, −33, and −1,500 kPa (−0.10, −0.33, and −15 bar) of suction were plotted over the moisture retention curves to show the contrast between the derived and measured moisture contents. In Table C-2, reproduced from DTN: MO0608SPANYECT.000, the analysis files are listed.

Table C-2. Analysis File Descriptions

File	Description
NyeCounty_Hanford_DataMatch_August22_2006.xls	Soil hydraulic properties derived from Hanford database and Nye County textural data.
NyeCounty_MethodCorroboration_August1_2006.xls	Soil hydraulic properties derived from Rawls and Brakensiek and ROSETTA using Nye County soils data. Comparison made between three pedotransfer function methods.
MoistureRetentionCurve_MethodCorroboration_August22_2006.xls	Moisture retention curves using van Genuchten parameters derived from Nye County soil textures matched to Hanford soil textures.

Source: DTN: MO0608SPANYECT.000.

APPENDIX D

DISTRIBUTION EVALUATION

DISTRIBUTION EVALUATION

This appendix provides evaluations of parameter distributions for soil units in alternate soil groups 1 and 2. The parameters are FC, PWP, WHC, and θ_s, which are all measurements of soil moisture content. Saturated hydraulic conductivity is not considered because it was established to be lognormally distributed (Section 6.3.4).

Alternate soil group 1 consists of four soil units: Soil Unit 1, Soil Unit 2-6, Soil Unit 3-4, and Soil Unit 5-7-9 (Section 6.2.5). Histograms are presented from each parameter and each soil unit (Figures D-1 through D-4). Normal and lognormal distributions fits are included on the histograms and tested for goodness-of-fit with Shapiro-Wilk W test and KSL test, respectively. These tests provide an indication of potential fit of the data to the distributions and indicate whether either or both distributions can be rejected (Figures D-1 through D-4). If the distribution is rejected, then it is not further considered. If it is not rejected, then it is further evaluated. A distribution, although not rejected by the goodness-of-fit tests, may not be appropriate if values at the extreme range of the distribution are physically unrealistic.

Extreme range is defined as the minimum value at minus two standard deviations from the mean value and the maximum value at plus two standard deviations from the mean value (Table D-1). Minimum values that are negative are physically unrealistic because soil moisture can never be less than zero. Maximum values of 1 or greater are physically unrealistic because at a value of 1 there would be only water. The mean and standard deviation are provided (Table D-1) for data that have been fit to either normal or lognormal distributions and not rejected by the goodness-of-fit tests. Data that do not fit either normal or lognormal distributions, based on the goodness-of-fit tests and examination of extreme values, are fit to beta distributions (Figures D-5 through D-7). The beta-fitting parameters are also provided on these figures.

Alternate soil group 2 consists of one soil unit in which all the soils in the infiltration model area are combined. Histograms are presented from each parameter for the one soil unit (Figure D-8). Normal and lognormal distributions fits are included on the histograms and tested for goodness-of-fit with Shapiro-Wilk W test and KSL test, respectively. Neither normal nor lognormal distributions are rejected by these tests. The values at the extreme range are examined (Table D-2). Based on examination, all normal distributions are rejected because the values at the mean minus two standard deviations are all negative, which is physically impossible. All lognormal distributions are accepted because the minimum and maximum values in the distribution are physically possible.

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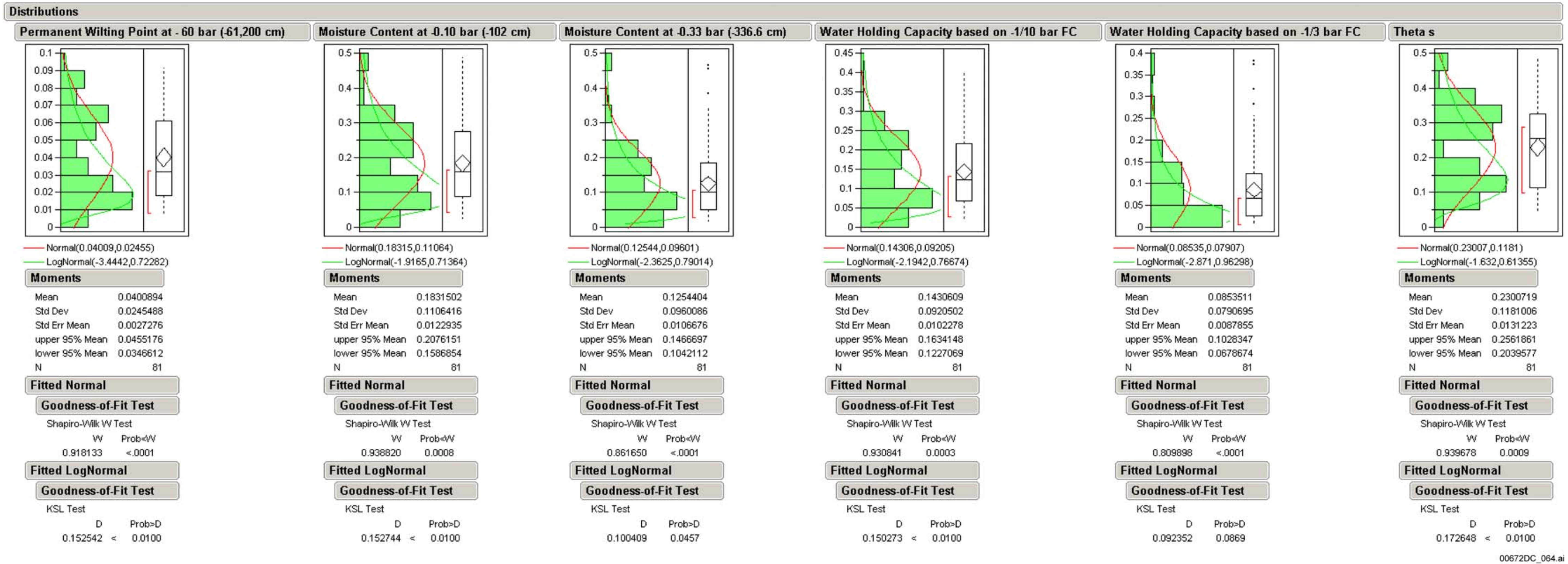

Figure D-1. Histograms, Fitted Normal and Lognormal Distributions, and Goodness-of-fit Tests for Soil Unit 1

Source: Output DTN: MO0605SEPALTRN.000.

NOTE: Developed with *JMP® Version 5*, Release 5.1.

FC = field capacity.

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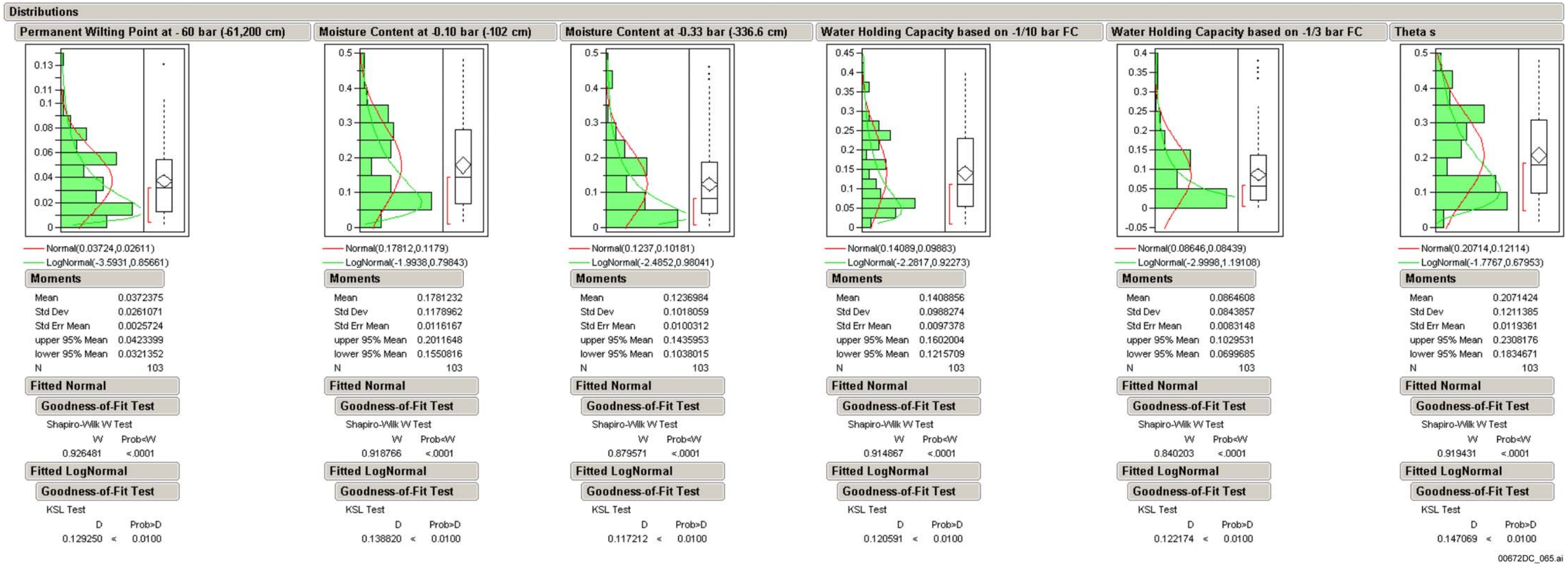

Figure D-2. Histograms, Fitted Normal and Lognormal Distributions, and Goodness-of-fit Tests for Soil Unit 2-6

Source: Output DTN: MO0605SEPALTRN.000.

NOTE: Developed with *JMP® Version 5*, Release 5.1.

FC = field capacity.

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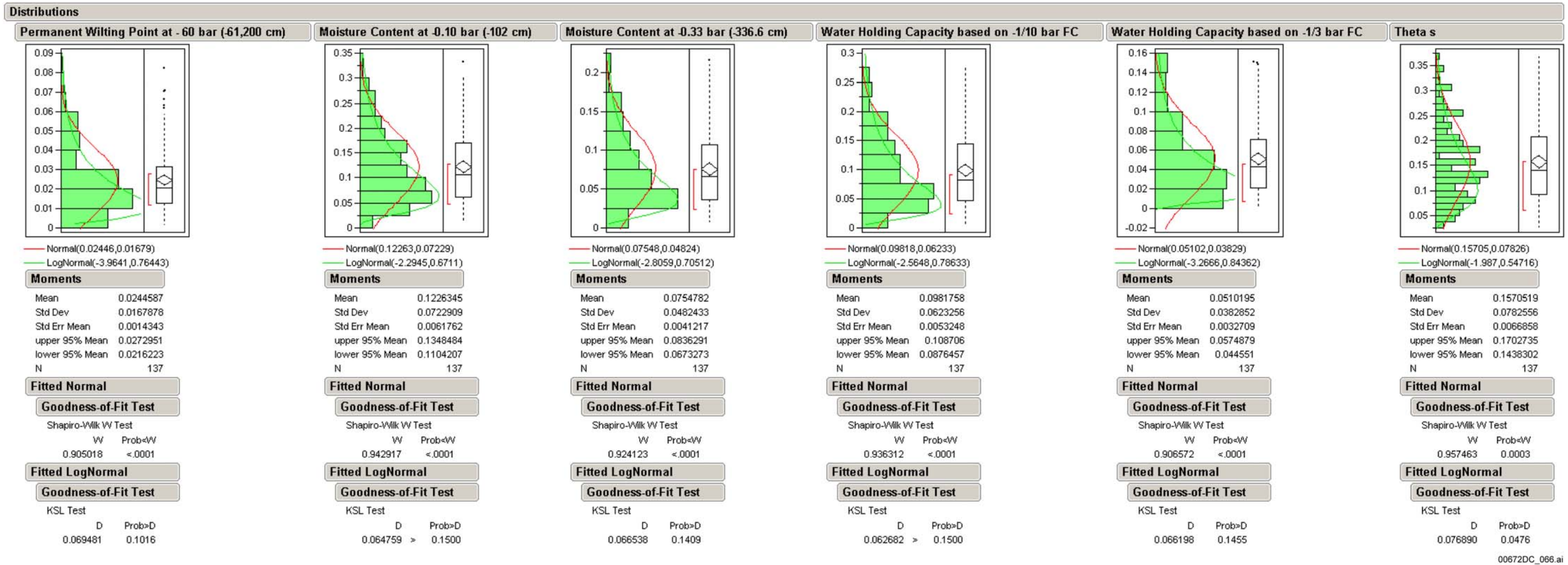

Figure D-3. Histograms, Fitted Normal and Lognormal Distributions, and Goodness-of-fit Tests for Soil Unit 3-4

Source: Output DTN: MO0605SEPALTRN.000.

NOTE: Developed with *JMP® Version 5*, Release 5.1.

FC = field capacity.

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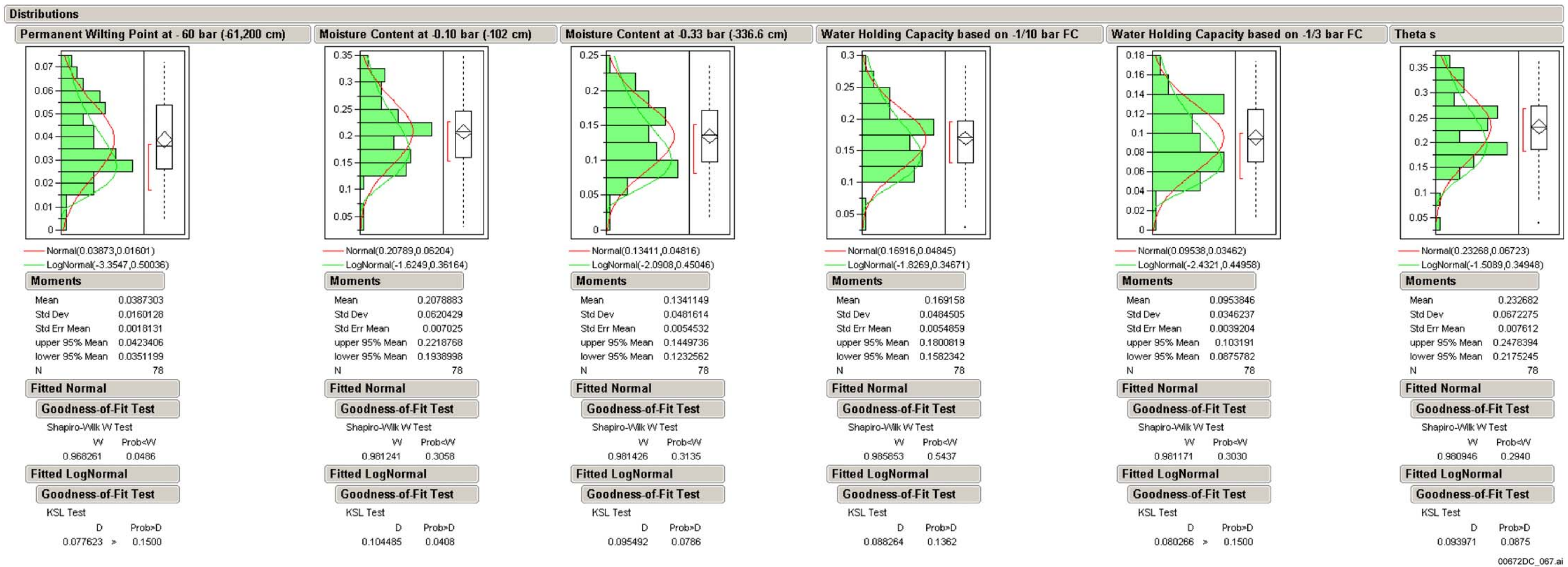

Figure D-4. Histograms, Fitted Normal and Lognormal Distributions, and Goodness-of-fit Tests for Soil Unit 5-7-9

Source: Output DTN: MO0605SEPALTRN.000.

NOTE: Developed with *JMP® Version 5*, Release 5.1.

FC = field capacity.

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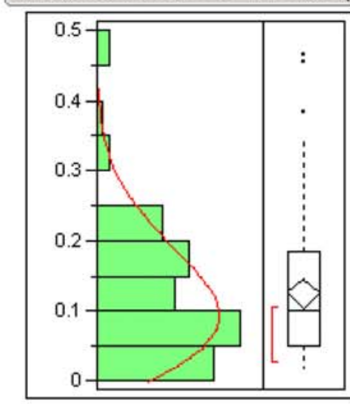
Distributions

Moisture Content at -0.33 bar (-336.6 cm)



Moments

Mean	0.1254404
Std Dev	0.0960086
Std Err Mean	0.0106676
upper 95% Mean	0.1466697
lower 95% Mean	0.1042112
N	81

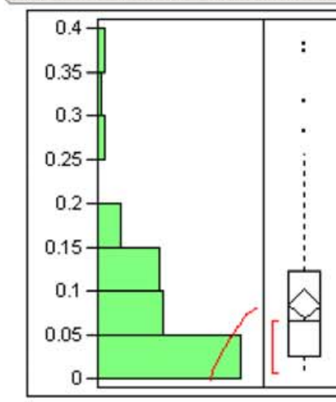
Fitted Beta

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	4.3811	.	.
Shape	Beta	18.4854	.	.
Threshold	Theta	-0.0820	.	.
Scale	Sigma	1.0894	.	.

Note: unable to converge on all confidence limits.

Water Holding Capacity based on -1/3 bar FC



Moments

Mean	0.0853511
Std Dev	0.0790695
Std Err Mean	0.0087855
upper 95% Mean	0.1028347
lower 95% Mean	0.0678674
N	81

Fitted Beta

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	0.55542	.	.
Shape	Beta	-3.79322	.	.
Threshold	Theta	-0.09460	.	.
Scale	Sigma	0.79286	.	.

Note: unable to converge on all confidence limits.

00672DC_068.ai

Figure D-5. Histograms, Fitted Beta Distribution and Distribution Parameters for Soil Unit 1, Alternate Soil Group 1

Source: Output DTN: MO0605SEPALTRN.000.

NOTES: Developed with *JMP® Version 5*, Release 5.1.

Field capacity at −0.33 bar and water holding capacity at −0.33 bar are fitted to Beta distributions; the other parameters are fitted to lognormal distributions.

FC = field capacity.

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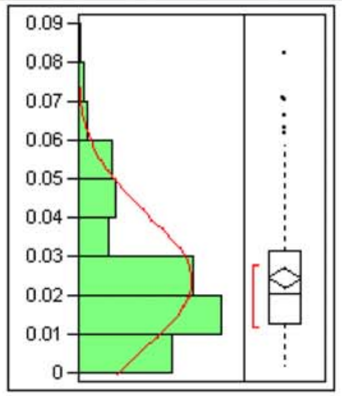
Distributions

Permanent Wilting Point at - 60 bar (-61,200 cm)



Beta(30.4468,39.6186,-0.098,0.282)

Moments

Mean	0.0244587
Std Dev	0.0167878
Std Err Mean	0.0014343
upper 95% Mean	0.0272951
lower 95% Mean	0.0216223
N	137

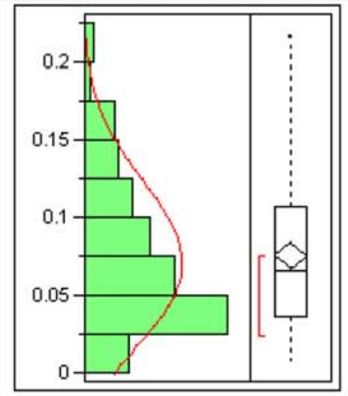
Fitted Beta

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	30.4468	.	.
Shape	Beta	39.6186	.	.
Threshold	Theta	-0.0980	.	.
Scale	Sigma	0.2820	.	.

Note: unable to converge on all confidence limits.

Moisture Content at -0.33 bar (-336.6 cm)



Beta(7.21711,10.6346,-0.0919,0.4158)

Moments

Mean	0.0754782
Std Dev	0.0482433
Std Err Mean	0.0041217
upper 95% Mean	0.0836291
lower 95% Mean	0.0673273
N	137

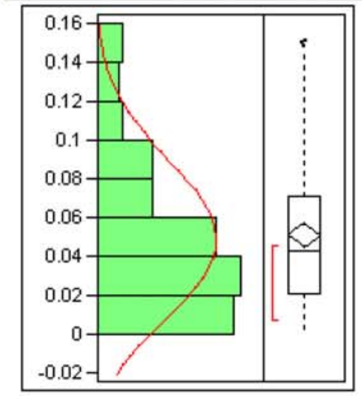
Fitted Beta

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	7.2171	.	.
Shape	Beta	10.6346	.	.
Threshold	Theta	-0.0919	.	.
Scale	Sigma	0.4158	.	.

Note: unable to converge on all confidence limits.

Water Holding Capacity based on -1/3 bar FC



Beta(8.8309,11.6016,-0.1,0.35075)

Moments

Mean	0.0510195
Std Dev	0.0382852
Std Err Mean	0.0032709
upper 95% Mean	0.0574879
lower 95% Mean	0.044551
N	137

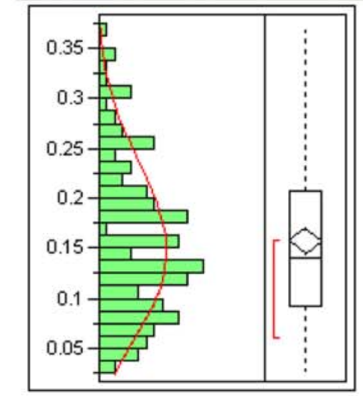
Fitted Beta

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	8.8309	.	.
Shape	Beta	11.6016	.	.
Threshold	Theta	-0.1000	.	.
Scale	Sigma	0.3508	.	.

Note: unable to converge on all confidence limits.

Theta s



Beta(5.04306,7.35252,-0.073,0.5681)

Moments

Mean	0.1570519
Std Dev	0.0782556
Std Err Mean	0.0066858
upper 95% Mean	0.1702735
lower 95% Mean	0.1438302
N	137

Fitted Beta

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	5.04306	.	.
Shape	Beta	7.35252	.	.
Threshold	Theta	-0.07304	.	.
Scale	Sigma	0.56810	.	.

Note: unable to converge on all confidence limits.

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Figure D-6. Histograms, Fitted Beta Distribution and Distribution Parameters for Soil Unit 3-4, Alternate Soil Group 1

Source: Output DTN: MO0605SEPALTRN.000.

NOTES: Developed with *JMP® Version 5*, Release 5.1.

Permanent wilting point, θs, field capacity at −0.33 bar, and water holding capacity at −0.33 bar are fitted to Beta distributions; the other parameters are fitted to lognormal distributions.

FC = field capacity.

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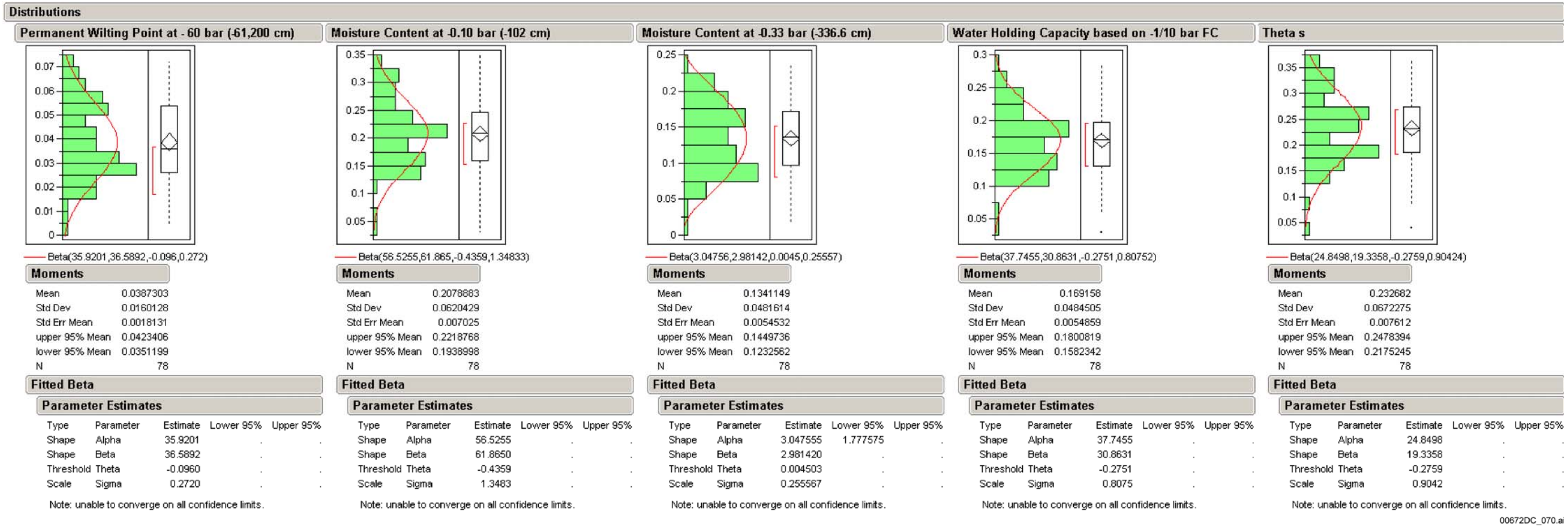

Moments

	Permanent Wilting Point at - 60 bar (-61,200 cm)	Moisture Content at -0.10 bar (-102 cm)	Moisture Content at -0.33 bar (-336.6 cm)	Water Holding Capacity based on -1/10 bar FC	Theta s
Mean	0.0387303	0.2078883	0.1341149	0.169158	0.232682
Std Dev	0.0160128	0.0620429	0.0481614	0.0484505	0.0672275
Std Err Mean	0.0018131	0.007025	0.0054532	0.0054859	0.007612
upper 95% Mean	0.0423406	0.2218768	0.1449736	0.1800819	0.2478394
lower 95% Mean	0.0351199	0.1938998	0.1232562	0.1582342	0.2175245
N	78	78	78	78	78

Fitted Beta — Parameter Estimates

Permanent Wilting Point at - 60 bar (-61,200 cm)

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	35.9201	.	.
Shape	Beta	36.5892	.	.
Threshold	Theta	-0.0960	.	.
Scale	Sigma	0.2720	.	.

Note: unable to converge on all confidence limits.

Moisture Content at -0.10 bar (-102 cm)

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	56.5255	.	.
Shape	Beta	61.8650	.	.
Threshold	Theta	-0.4359	.	.
Scale	Sigma	1.3483	.	.

Note: unable to converge on all confidence limits.

Moisture Content at -0.33 bar (-336.6 cm)

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	3.047555	1.777575	.
Shape	Beta	2.981420	.	.
Threshold	Theta	0.004503	.	.
Scale	Sigma	0.255567	.	.

Note: unable to converge on all confidence limits.

Water Holding Capacity based on -1/10 bar FC

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	37.7455	.	.
Shape	Beta	30.8631	.	.
Threshold	Theta	-0.2751	.	.
Scale	Sigma	0.8075	.	.

Note: unable to converge on all confidence limits.

Theta s

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	Alpha	24.8498	.	.
Shape	Beta	19.3358	.	.
Threshold	Theta	-0.2759	.	.
Scale	Sigma	0.9042	.	.

Note: unable to converge on all confidence limits.

Figure D-7. Histograms, Fitted Beta Distribution and Distribution Parameters for Soil Unit 5-7-9, Alternate Soil Group 1

Source: Output DTN: MO0605SEPALTRN.000.

NOTES: Developed with *JMP® Version 5*, Release 5.1.

Permanent wilting point, θs, field capacity at −0.33 bar, field capacity at −0.10 bar, and water holding capacity at −0.10 bar are fitted to Beta distributions; the other parameter, water holding capacity at −0.33 bar, is fitted to lognormal distributions.

FC = field capacity.

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Table D-1. Evaluation of Normal and Lognormal Distribution Fits for Hydraulic Parameters in Alternate Soil Group 1

	Statistic for Normal Distribution					**Statistic for Lognormal Distribution**						
	Mean	**SD**	**Mean minus 2 SD**	**Mean Plus 2 SD**	**Normal Fit (Yes/No)**	**Mean for Ln-Transformed Data**	**SD for Ln-Transformed Data**	**Mean Minus 2 SD Based on Ln-Transformed Data**	**Mean Minus 2 SD Based on Un-Transformed Data**	**Mean Plus 2 SD Based on Ln-Transformed Data**	**Mean Plus 2 SD based on Un-Transformed Data**	**Log-normal Fit (Yes/No)**
Soil Unit 1												
PWP	0.040089	0.024549	–0.009	0.089	No	–3.4442104	0.72281719	–4.890	0.008	–1.999	0.136	Yes
θ_s	NA	NA	NA	NA	No	–1.6319563	0.61354509	–2.859	0.057	–0.405	0.667	Yes
FC at –0.33 bar	0.12544	0.096009	–0.067	0.317	No	NA	NA	NA	NA	NA	NA	No
FC at –10 bar	NA	NA	NA	NA	No	–1.9164747	0.71364172	–3.344	0.035	–0.489	0.613	Yes
WHC at –0.33 bar	0.085351	0.079069	–0.073	0.243	No	NA	NA	NA	NA	NA	NA	No
WHC at –0.10 bar	NA	NA	NA	NA	No	–2.1942439	0.76674325	–3.728	0.024	–0.661	0.516	Yes
Soil Unit 2-6												
PWP	0.037	0.026	–0.015	0.089	No	–3.593	0.857	–5.306	0.005	–1.880	0.153	Yes
θ_s	0.207	0.121	–0.035	0.449	No	–1.777	0.680	–3.136	0.043	–0.418	0.659	Yes
FC at –0.33 bar	0.124	0.102	–0.080	0.327	No	–2.485	0.980	–4.446	0.012	–0.524	0.592	Yes
FC at –10 bar	0.178	0.118	–0.058	0.414	No	–1.994	0.798	–3.591	0.028	–0.397	0.672	Yes
WHC at –0.33 bar	0.086	0.084	–0.082	0.255	No	–3.000	1.191	–5.382	0.005	–0.618	0.539	Yes
WHC at –0.10 bar	0.141	0.099	–0.057	0.339	No	–2.282	0.923	–4.127	0.016	–0.436	0.646	Yes

Table D-1. Evaluation of Normal and Lognormal Distribution Fits for Hydraulic Parameters in Alternate Soil Group 1 (Continued)

	Statistic for Normal Distribution					**Statistic for Lognormal Distribution**						
	Mean	**SD**	**Mean minus 2 SD**	**Mean Plus 2 SD**	**Normal Fit (Yes/No)**	**Mean for Ln-Transformed Data**	**SD for Ln-Transformed Data**	**Mean Minus 2 SD Based on Ln-Transformed Data**	**Mean Minus 2 SD Based on Un-Transformed Data**	**Mean Plus 2 SD Based on Ln-Transformed Data**	**Mean Plus 2 SD based on Un-Transformed Data**	**Log-normal Fit (Yes/No)**
Soil Unit 3-4												
PWP	0.024459	0.016788	–0.009	0.058	No	NA	NA	NA	NA	NA	NA	No
θ_s	NA	NA	NA	NA	No	NA	NA	NA	NA	NA	NA	No
FC at –0.33 bar	0.075478	0.048243	–0.021	0.172	No	NA	NA	NA	NA	NA	NA	No
Soil Unit 3-4 (Continued)												
FC at –10 bar	0.122635	0.072291	–0.022	0.267	No	–2.2945455	0.67110479	–3.637	0.026	–0.952	0.386	Yes
WHC at –0.33 bar	0.051019	0.038285	–0.026	0.128	No	NA	NA	NA	NA	NA	NA	No
WHC at –0.10 bar	0.098176	0.062326	–0.026	0.223	No	–2.565	0.78632629	–4.137	0.016	–0.992	0.371	Yes
Soil Unit 5-7-9												
PWP	NA	NA	NA	NA	No							
θ_s	NA	NA	NA	NA	No	NA	NA	NA	NA	NA	NA	No
FC at –0.33 bar	NA	NA	NA	NA	No	NA	NA	NA	NA	NA	NA	No
FC at –10 bar	NA	NA	NA	NA	No	NA	NA	NA	NA	NA	NA	No
WHC at –0.33 bar	NA	NA	NA	NA	No	–3.355	0.500	–4.355	0.013	–2.354	0.095	Yes

Table D-1. Evaluation of Normal and Lognormal Distribution Fits for Hydraulic Parameters in Alternate Soil Group 1 (Continued)

	Statistic for Normal Distribution					Statistic for Lognormal Distribution						
	Mean	**SD**	**Mean minus 2 SD**	**Mean Plus 2 SD**	**Normal Fit (Yes/No)**	**Mean for Ln-Transformed Data**	**SD for Ln-Transformed Data**	**Mean Minus 2 SD Based on Ln-Transformed Data**	**Mean Minus 2 SD Based on Un-Transformed Data**	**Mean Plus 2 SD Based on Ln-Transformed Data**	**Mean Plus 2 SD based on Un-Transformed Data**	**Log-normal Fit (Yes/No)**
Soil Unit 5-7-9 (Continued)												
WHC at –0.10 bar	NA	NA	NA	NA	No	NA	NA	NA	NA	NA	NA	No

Source: Output DTN: MO0605SEPALTRN.000.

NOTES: Alternate soil group 2 includes all soils in the infiltration model area.

NA = Not applicable because the Shapiro-Wilk W test for normality indicated the data were not normally distributed or the KSL test for lognormal indicated the distribution was not lognormally distributed.

Results of the Shapiro-Wilk W test and the KSL test and histograms are provided on Figures D-1 to D-4.

FC = field capacity; PWP = permanent wilting point; SD = standard deviation; WHC = water holding capacity.

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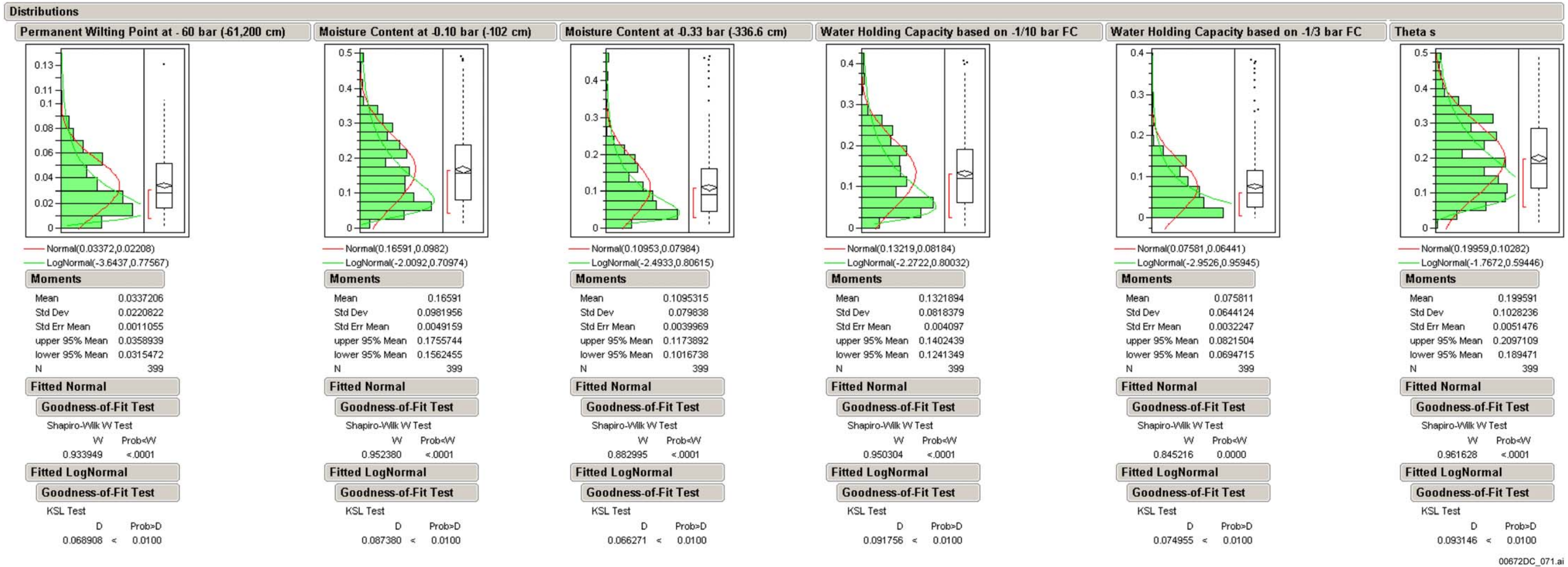

Figure D-8. Histograms, Fitted Normal and Lognormal Distributions, and Goodness-of-fit Tests for Alternate Soil Group 2 (All Yucca Mountain Soils)

Source: Output DTN: MO0605SEPALTRN.000.

NOTE: Developed with *JMP® Version 5*, Release 5.1

FC = field capacity.

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Table D-2. Evaluation of Normal and Lognormal Distribution Fits for Hydraulic Parameters in Alternate Soil Group 2

	Statistic for Normal Distribution					**Statistic for Lognormal Distribution**						
	Mean	**SD**	**Mean Minus 2 SD**	**Mean Plus 2 SD**	**Normal Fit (Yes/No)**	**Mean for Ln-Transformed Data**	**SD for Ln-Transformed Data**	**Mean Minus 2 SD Based on Ln-Transformed Data**	**Mean Minus 2 SD Based on Un-Transformed Data**	**Mean Plus 2 SD Based on Ln-Transformed Data**	**Mean Plus 2 SD Based on Un-Transformed Data**	**Lognormal Fit (Yes/No)**
PWP	0.034	0.022	–0.010	0.078	No	–3.644	0.776	–5.195	0.006	–2.092	0.123	Yes
θ_s	0.200	0.103	–0.006	0.405	No	–1.767	0.594	–2.956	0.052	–0.578	0.561	Yes
FC at –0.33 bar	0.110	0.080	–0.050	0.269	No	–2.493	0.806	–4.106	0.016	–0.881	0.414	Yes
FC at –10 bar	0.166	0.098	–0.030	0.362	No	–2.009	0.710	–3.429	0.032	–0.590	0.554	Yes
WHC at –0.33 bar	0.076	0.064	–0.053	0.205	No	–2.953	0.959	–4.871	0.008	–1.034	0.356	Yes
WHC at –0.10 bar	0.132	0.082	–0.031	0.296	No	–2.272	0.800	–3.873	0.021	–0.672	0.511	Yes

Source: Output DTN: MO0605SEPALTRN.000.

NOTES: Alternate soil group 2 includes all soils in the infiltration model area.

Results of the Shapiro-Wilk W test and the KSL test and histographs are provided on Figure D-5.

FC = field capacity; PWP = permanent wilting point; SD = standard deviation; WHC = water holding capacity.

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